AD NUMBER

AD853233

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; APR 1969. Other requests shall be referred to Air Force Rocket Propulsion Lab., Attn: RPOR/STINFO, Edwards AFB, CA 93523.

AUTHORITY

Air Force Rocket Propulsion Lab. ltr dtd 29 Sep 1971

AFRPL-TR-69-48

AD853233

INJECTION AND COMBUSTION OF HYPERGOLIC PROPELLANTS

PART I REACTIVE STREAM IMPINGEMENT

PART II EXTENSION OF STEADY-STATE COMBUSTION MODEL

APRIL 1969

BY

B.P. BREEN, L.B. ZUNG, AND B.R. LAWVER

T.C. KOSVIC AND D.E. COATS

DYNAMIC SCIENCE

A Division of Marshall Industries

Monrovia, California

AIR FORCE ROCKET PROPULSION LABORATORY

DIRECTORAGE OF LABORATORIES

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

EDWARDS, CALIFORNIA

SPECIAL NOTICE

When U.S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

INJECTION AND COMBUSTION OF HYPERGOLIC PROPELLANTS

Part I Reactive Stream Impingement

Part II Extension of Steady-State Combustion Model

April 1969

Final Technical Report F04611-68-C-0040

By

B. P. Breen, L. B. Zung, and B. R. Lawver
T. C. Kosvic and D. E. Coats
DYNAMIC SCIENCE, a Division
of Marshall Industries
Monrovia, California

For

AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTORATE OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS AIR FORCE BASE, CALIFORNIA

FOREWORD

The research documented in this final report was sponsored by the Air Force Rocket Propulsion Laboratory, Directorate of Laboratories, Edwards, California, under Contract F04611-68-C-0040. The program was conducted by the Dynamic Science Division of Marshall Industries under the direction of Captain C. J. Abbe, Air Force Project Officer.

The Dynamic Science Program Manager was Dr. B. P. Breen and the Project Engineers were Mr. B. R. Lawver, Dr. L. B. Zung and Mr. T. C. Kosvic. Under Part I of the program, the efforts of Mr. Robert Wheelock of Wyle Laboratories (NORCO facility), and Mr. John White, Mr. Wm. Irwin and Mr. W. Yoshida of Dynamic Science, are acknowledged. Under Part II of the program, Capt. C. J. Abbe, Dr. J. O'Hara, and Mr. G. Langberg of the AFRPL and Mr. D. E. Coats of Dynamic Science contributed to the effort.

This technical report has been reviewed and is approved.

C. J. Abbe, Capt, USAF
Senior Project Officer

SUMMARY

The impingement of liquid hypergolic propellants following mixing and separation mechanisms is characterized by chemical reaction time and residence time criteria. Experimental results, obtained by hydrazine impinging with nitrogen tetroxide, agree very well with the limit defined by assuming that separation occurs when residence time is greater than reaction time. This criteria shows a strong influence of propellant temperature because reaction time is exponentially dependent upon temperature in this ignition region (the existence of an ambient temperature ignition region is the essence of the meaning of hypergolicity). Further experimental results indicate that chamber pressure had only a second order effect and that monomethyl hydrazine and UDMH/hydrazine (50/50 blend) impinging with nitrogen tetroxide separate at higher propellant temperatures than those obtained for the hydrazine-nitrogen tetroxide combination. Stream separation always occurred when impinging hydrazine with compound A ($C\ell F_5$) in the experimental fuel and oxidizer temperature range (hydrazine -40 to 60°F with compound A - 0 to 30°F).

A second work area of the project concerned the extension of the Steady-State Combustion Computer Model undertaken as a joint technical effort between the Air Force Rocket Propulsion Laboratory and Dynamic Science. The computer program was generalized to allow increased versatility in running various propellant systems. The numerical procedures and organization of the program were substantially improved. Propellant property values were gathered for several systems of current interest. A computer program listing is presented.

TABLE OF CONTENTS

Figures (Continued)

PART I. REACTIVE STREAM IMPINGEMENT

1. INTRODUCTION

The work reported here involves an experimental determination of the physical and design parameters which control the mechanisms of hypergolic propellant stream impingement. The need and usefulness for this work is discussed and a physical picture of hypergolic impingement was developed. This picture led to a model of hypergolic stream mixing reaction and blow-apart criteria and the criteria were used to define an experimental technique involving photographic observation of the impingement plane. Mix/separate criteria were measured for nitrogen tetroxide impingement with hydrazine, MMH, and 50-50 (hydrazine-UDMH). Compound A (ClF_5) was also investigated and photographically observed. The results of the experimental criteria were applied to demonstrate their effect on rocket engine design and were compared to large scale engine performance and injection mixing explosion measurements.

a. Propellant Injector Design

Injection spray patterns control O/F mixing and mass distribution within a rocket engine combustion chamber and, consequently, these spray patterns exert a major design influence over chamber performance, thrust chamber liner compatibility and combustion instability. Injector design was largely a matter of intuition and trial and error testing until the early work of Rupe, (Ref. 1) demonstrated the possibility of defining the relationship of design parameters to the uniformity of stream mixing. The mixing uniformity criteria were developed by Rupe for nonreactive impingement and involved two phases of injector design: first, the spray pattern emanating from the individual set of impinging elements must be defined in terms of the design parameters which affect impingement characteristics and, secondly, all the spray patterns together must be layed-out to give the most uniform mass flux within the constraint of the design manifolding. Design of unlike hypergolic injectors has remained a matter of trial and error, however, because the first phase determination, that of the spray pattern emanating from the individual set of unlike hypergolic impinging elements, has not been defined in terms of the design and operating parameters which affect impingement characteristics.

b. Hypergolic Impingement

The question which must be answered before trial and error testing of hypergolic injectors will lead to any fruitful intuition is: Do hypergolic streams mix nonreactively or do they always separate (i.e., blow apart), or perhaps for different critical stream parameters is there mix/separate criteria? Previous work has indicated that hypergolic streams sometimes mix and sometimes separate. It was the purpose of this work, therefore, to experimentally define which parameters are most influential in defining the mix/separate phenomena of several hypergolic combinations.

In any impingement and atomization scheme the mixing uniformity would appear to be important and it can be related to a ratio such as the streams' momentum or stagnation pressures which involve the density, ρ; velocity, v; and orifice diameter, D. Now, for extension to hypergolic streams, the basic nature of hypergolicity must be considered as it involves chemical kinetics (exponentially influenced by temperature, T) and residence time within a heat balance control

volume. Another system parameter which affects chemical kinetics is chamber pressure, while orifice hydraulics (L/D) always affect turbulence level and mixing. Having listed these parameters, it is easily seen why trial and error engine testing of hypergolic impingement efficiency and popping has not been fruitful: the chemical kinetics of hypergolicity are exponentially temperature dependent while in full scale engine test programs this parameter is seldom considered; it is often not controlled from run-to-run; and is also often not even measured or available in data reduction.

c. <u>Previous Work</u>

Early investigations in this field have tended to be phenomenologically oriented. Thus, the work reported by Elverum and Staudhammer (Ref. 2), and Johnson (Ref. 3) noted that streams do separate and they continued to show the magnitude of the effect. The later work of Burrows (Ref. 4) gave indication that hypergolic streams do not always separate and measured specific conditions necessary for separation to occur. More extensive work has been carried out by Lawver and Breen (Ref. 5) to define regimes of stream mixing and separation. Their experiments used photographic observation of the actual impingement plane under a transparent window and correlation of the observed regime with the parameters of temperature and flow residence time. A review of the problem was presented by Kushida and Houseman (Ref. 6), where an analytical model was developed to predict mix/separate criteria in terms of pressure, temperature and impingement plane contact time. This model of liquid phase impingement made use of the heat release rate measurements of Feiler and Somogyi (Ref. 7), and involved a sensible heat balance between Feiler's heat release rate and the heat required to raise the liquid to its boiling point. The model presented by Lawver and Breen (Ref. 4) and that presented by Kushida and Houseman (Ref. 6) are different in that the first shows an exponential importance of temperature upon the reaction rate while the second shows a linear temperature effect in the boiling point heat balance, using a maximum heat release rate from Feiler and Somogyi. It was more the point of view of Lawver and Breen, and is expressed in Feiler's report, that the heat release rate shows a sharp change in temperature which should correspond to the inception of stream separation.

d. <u>Summary of this Experimental Work</u>

The experimental techniques developed by Lawver and Breen in Reference 5 were extended to allow high pressure (500 psia) operation with the family of hydrazine fuels N_2O_4 and compound A oxidizers. Experimental data were thus obtained showing the effect of velocity, orifice diameter, propellant temperature, impingement angle and chamber pressure. These curves define criteria which can be used by the design engineer to determine if hypergolic impingement spray pattern is within the mixed zone or the separate zone. At longer residence times, popping phenomenon was also encountered and the regions of popping are shown for the hydrazine, MMH, and 50-50 fuels impinging on N_2O_4. A great many experimental difficulties were encountered in the observation of the compound A hydrazine impingement plane, but it appeared that the streams always separated within the limited range of temperature data.

The mix/separate criteria are reviewed in a discussion of their application. The popping phenomenon, observed at long residence time, has also been observed in engine test programs such as that reported by Weiss and Klopotek (Ref. 8) and extensively investigated by Clayton (Ref. 9). Beyond the immediate

injector design, the fact of impingement regime is also discussed as it affects such steady state combustion profile calculations as those reported by Dynamic Science (Ref. 10) and currently being successfully used to correlate engine stability by Abbe (Ref. 11).

2. IMPINGEMENT OF HYPERGOLIC STREAMS

Both research projects and full-scale engine firings with hypergolic propellant combinations have demonstrated that the unlike streams sometimes mix and sometimes separate causing large changes in injector and combustor performance. From previous work it is possible to develop a physical picture of the mix/separate phenomena and to transform this picture or model into analytical expressions defining the controlling parameters of chemical kinetics, residence time, and mixing.

a. The Physical Picture

For unlike impinging hypergolic streams, engine efficiency depends upon the degree of individual doublet mixing or separation, because generally secondary fan and droplet mixing is ineffective. This fact is demonstrated by the photographic comparison of the two different injection schemes studied by Marshall Burrows (Ref. 4). Figure 1a is a 6000 frame per second photograph of the hydrazine side of a quadruple impinging jet injector of 90° included angle while Figure 1b is the same injection scheme from N_2O_4 side. The injection scheme breaks the chamber into four quadrants as shown in Figures 1a and 1b. The N_2O_4 droplet vaporization causes the dark brown cloud of Figure 1b to exist axially down the chamber; the colorless hydrazine vapor of Figure 1a combusts sooner because of the tendency for hydrazine to decompose in high temperature environments. In both cases the combustion is efficient and is controlled by droplet vaporization. However, for the different injection scheme shown in Figure 1c the chamber is broken into only two halfs and the N_2O_4/N_2H_4 systems separate or blow apart. The lack of O/F and mass distribution uniformity causes secondary gas mixing to control the combustion and the resulting stratified flow causes droplet vaporization throughout the chamber to be inefficient because of low temperatures and nonstoichiometric combustion.

Observation of this separation and stratification problem led to the realization that it would be necessary to observe the details of the phenomena within the impingement plane and to experimentally define the controlling parameters.

A general and complete description near the stagnation point of impinging streams of hypergolic propellants requires a basic understanding of the interrelationships of propellant reaction kinetics and hydrodynamic flow properties. In more detail, the reaction kinetics involve:

The rate of liquid phase reaction,

The rate of gas phase reaction,

The rate of heat release, and

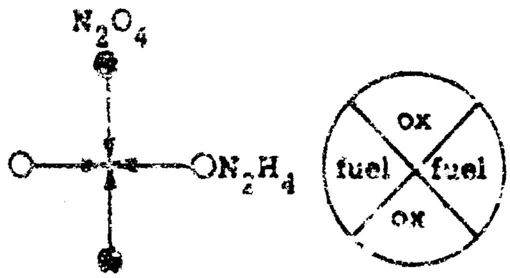
The rate of gas evolution.

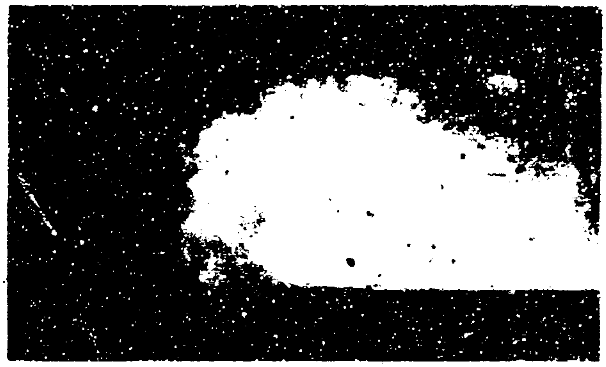
Aside from the stability problem associated with the fluid flow, important kinematic parameters are:

The degree of mixing,

The characteristic mixing time, and

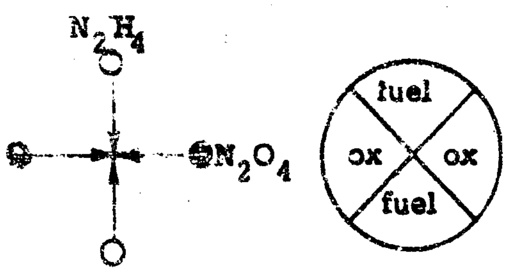
The residence time.

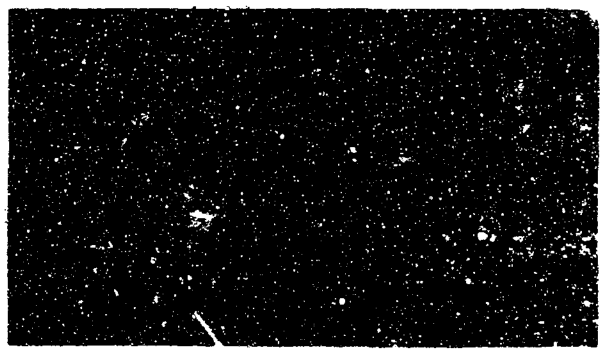




End view of impingement and resulting chamber quadrants

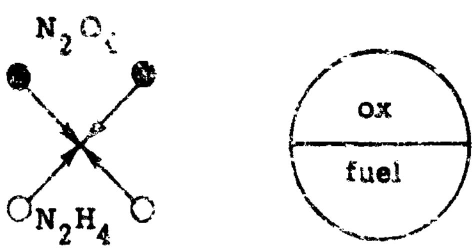
Figure 1a. Efficient N_2O_4/N_2H_4 Combustion from the Hydrazine Side.

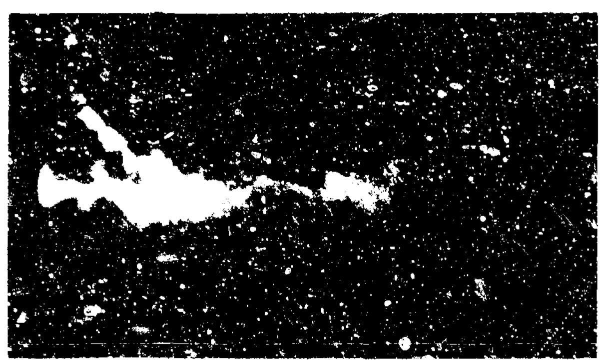




End view of impingement and resulting chamber quadrants

Figure 1b. The same Combustor as in Figure 1a showing Efficient N_2O_4/N_2H_4 Combustion from the Nitrogen Tetroxide Side.





End view of impingement and resulting chamber quadrants

Figure 1c. Inefficient N_2O_4/N_2H_4 Combustion and Stratification Caused by Hypergolic Stream Impingement and Blow Apart.

Figure 1. The Effect of Impingement on Stream Blow Apart and Combustor Efficiency. (Ref. 13.)

The condition of jet separation can be viewed as the occurrence of a locally strong exothermic reaction, liberating sufficient heat and gas that the streams are blown apart before substantial mixing has taken place. This locally strong exothermic reaction is more likely to take place close to the stagnation point for it is there the propellants experience the longest residence time. Thus when initial surface mixing first occurs near the stagnation point and the chemical reaction rate is fast enough to liberate sufficient heat and gas before substantial mixing has taken place downstream of the stagnation point separated flow results. When reaction is slow enough to allow a certain degree of mixing to first take place, a uniform combustion spray pattern appears. This physical picture has developed from experimental observation of the impingement plane during research performed on contract NAS7-467 (Ref. 5). Typical separated and mixed flow patterns are shown in Figure 2a and 2b. The propellant systems are hydrazine and nitrogen tetroxide.

b. <u>Data Correlation</u>

The criteria of stream separation has been described in detail in Reference 5 as a comparison of two characteristic times, namely the chemical kinetic time constant, τ_{chm}, and the common interfacial residence time between the two streams, τ_{res}. The critical chemical reaction time, τ_{chm}, is the time required for the chemical reaction to liberate sufficient heat and product gas to cause the streams to separate. This time constant is very sensitive to temperature because by the very definition of hypergolicity, a "runaway" ignition temperature exists within the range of ambient propellant temperatures. The interfacial residence time, τ_{res}, is characterized by the geometry and velocity of the flow. Separation or mixing phenomena depend on whether τ_{chm} is either smaller (separate) or greater (mix) than τ_{res}. The limit for chemical reaction, blow-apart, and separation is defined when τ_{res} is equal to τ_{chm}.

The chemical kinetic time constant may be obtained by approximating the rate of consumption of one of the propellant species by the first order decay:

$$\frac{dY}{dt} = -kY \tag{1}$$

where Y is the species concentration and k is the kinetic rate constant of the chemical reaction. Denoting Y_o as the initial propellant concentration, equation (1) gives:

$$\frac{Y}{Y_o} = e^{-kt} \tag{2}$$

and a characteristic time to ignition, τ_{chm}, may be defined when $Y/Y_o = e^{-1}$. For temperatures below the ignition temperature this time is very long, while for temperatures greater than the ignition temperature the time constant is much less than the characteristic mass transfer on heat transfer time constants. Thus for ignition phenomena to occur the value of the characteristic kinetic time constant shifts from rate-controlling (at low temperature) to not controlling over a small increment of temperature change and thus the ignition temperature is closely defined for any chosen value of Y/Y_o of the order of one. Thus τ_{chm} is defined from equation (2) as

$$\tau_{chm} = \frac{1}{k} \tag{3}$$

The reaction rate constant k may be assumed to follow the Arrhenius temperature dependence so that

$$\tau_{chm} = \frac{1}{A} e^{E/RT} \qquad (4)$$

Thus the characteristic time of chemical reaction is exponentially dependent upon temperature.

The characteristic residence time for which the streams are in forced mixing contact is a function of stream dimensions, velocity, and impingement angle. Characteristically this may be obtained from the geometry of the situation as:

$$\tau_{res} = \frac{D}{\sin(\theta/2)} \quad \frac{1}{V} \qquad (5)$$

where θ is the included angle of impingement, D is the orifice diameter, and V is the injected stream velocity.

Whenever the chemical time constant is less than or equal to the residence time the streams will tend to blow apart due to the tremendous heat release rates associated with the ignition and combustion of stoichiometric rocket propellants within the residence interface. Thus the separation limit is defined in terms of operating temperature and flow parameters by equating the two time constants

$$\frac{e^{E/RT}}{A} = \frac{D}{\sin(\theta/2)V} \qquad (6)$$

so that

$$\frac{D}{V} = [\frac{\sin(\theta/a)}{A}] \, e^{E/RT} \qquad (7)$$

or

$$\ell n \frac{D}{V} = \ell n \, [\frac{\sin(\theta/2)}{A}] + \frac{E}{R} \, \frac{1}{T} \qquad (8)$$

Postulation of the impingement process in terms of the physical parameters controlling reaction and stream separation indicates that the critical separation limit varies with D/V and is exponentially dependent upon 1/T. Thus experimental data are correlated on a semilogarithmic scale as proportional to the log D/V and inversely proportional to propellant temperature.

c. Injection Mixing Explosions

Another very critical problem associated with the impingement of hypergolic streams is concerned with the often observed explosions near the injector plate since they can act as initiation sources of detonation waves or "pops". Typical explosions of this kind were identified experimentally at Dynamic Science under NASA research contract NAS7-467 (Ref. 12) and are shown photographically in Figure 3. In contrast to the separation phenomena which are basically due to a locally strong exothermic reaction, explosions appear to be caused by ignition within the entire impingement region of mixed liquid ligaments. In this respect,

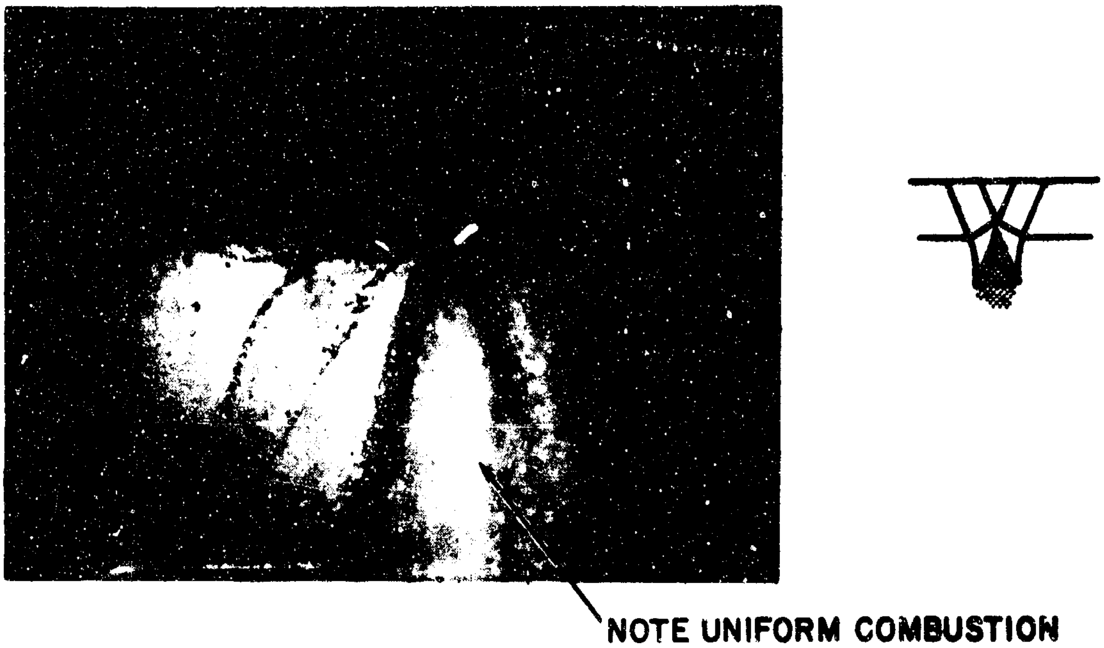
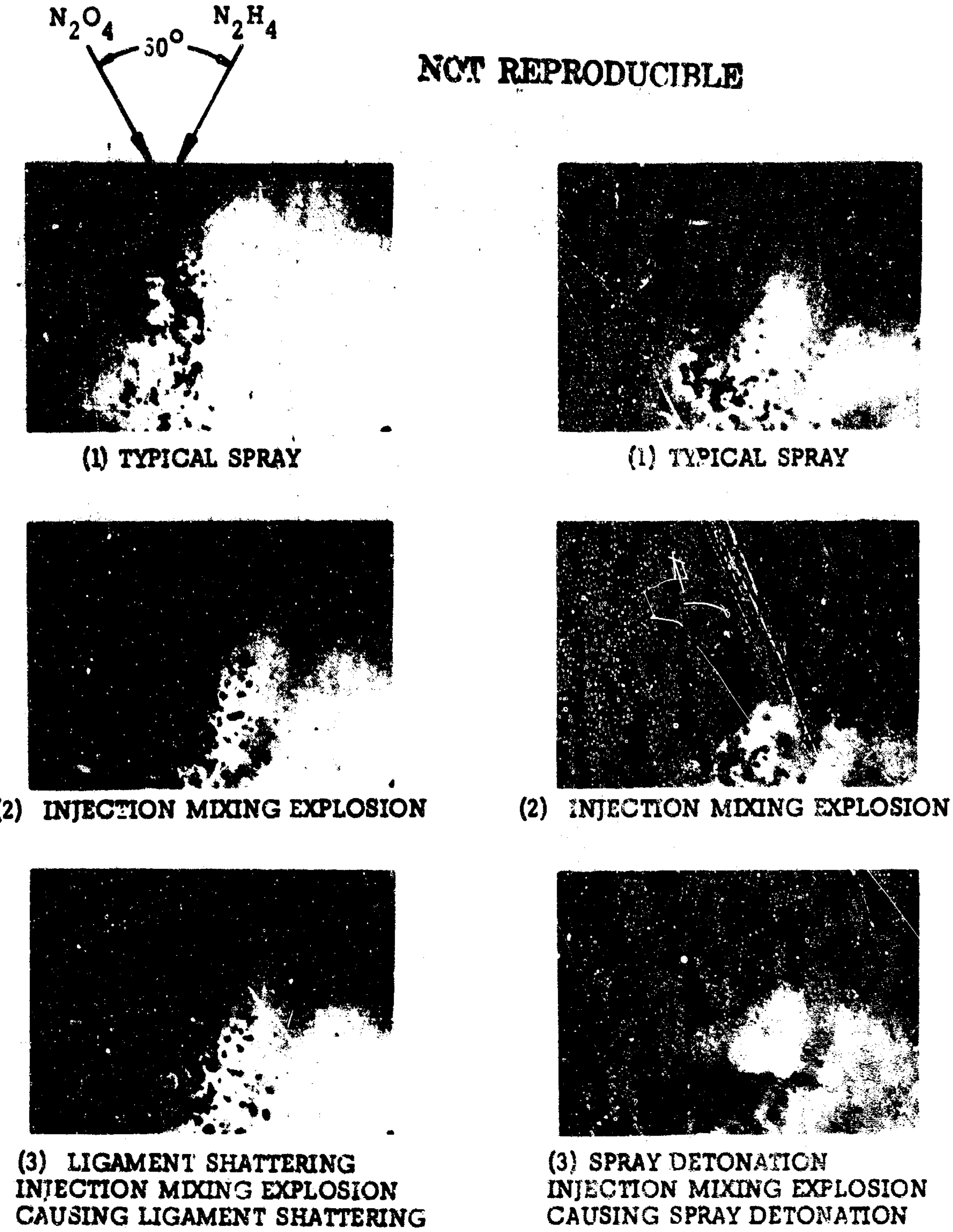


Figure 2a. Mixing and Uniform Spray Combustion of N_2O_4/N_2H_4 at 14°C. at 50 ft/sec and .050 inch Wide Stream.
Regime I-Mixing

Figure 2b. Hydrazine/Nitrogen Tetroxide Impingement 25°C at 100ft/sec and .100 inch Wide Stream.
Regime II-Separation



N_2H_4 VELOCITY = 25 ft/sec

N_2O_4 VELOCITY = 20 ft/sec

N_2H_4 ORIFICE DIA = .050"

N_2O_4 ORIFICE DIA = .050"

PROPELLANT TEMPERATURE 60°F

25 µsec EXPOSURE AT 2000 pic/sec

Figure 3. Injection Mixing Explosions Causing Ligament Shattering and Sometimes Spray Detonations (Taken from Reference 12).

injection mixing explosions depend very much on the degree of mixing of the impingement region. First of all the temperature must be low enough that mixing phenomena predominate then the degree of mixing of impinging jets depends on contact surface area, intrinsic turbulent levels and turbulent shear stresses. Extensive experimental work (Ref. 1) has been carried out to measure the mixing level of nonreactive impinging streams. Maximum mixing is observed when the quantity $\rho_1 U_1^2 D_1 = \rho_2 U_2^2 D_2$. ρ and U are the stream density and velocity. D is the orifice diameter. Based on experimental findings degree of mixing can be defined in terms of a nondimensional number δ.

$$\delta = \frac{1}{1 + \frac{\rho_1 U_1^2 D_1}{\rho_2 U_2^2 D_2}} \tag{9}$$

Uniform mixing occurs at $\delta = 0.5$. It is anticipated that for δ close to 0.5, injection mixing explosions are more likely to occur. Figure 4 shows regions of stream mixing and separation as well as injection mixing explosions as functions of propellant temperature, D/V, and degree of mixing arbitrarily defined in terms of δ.

The present experiment is designed to study stream mix/separate phenomena. Propellant temperature T and the mixing time D/V were accurately varied in order to investigate the relationship expressed in equation (8). Photographic observations of the impingement region were recorded to define the mix/separate phenomena. The measurement of injection mixing explosions was not the primary concern of this research but could be observed qualitatively from chamber pressure noise and roughness.

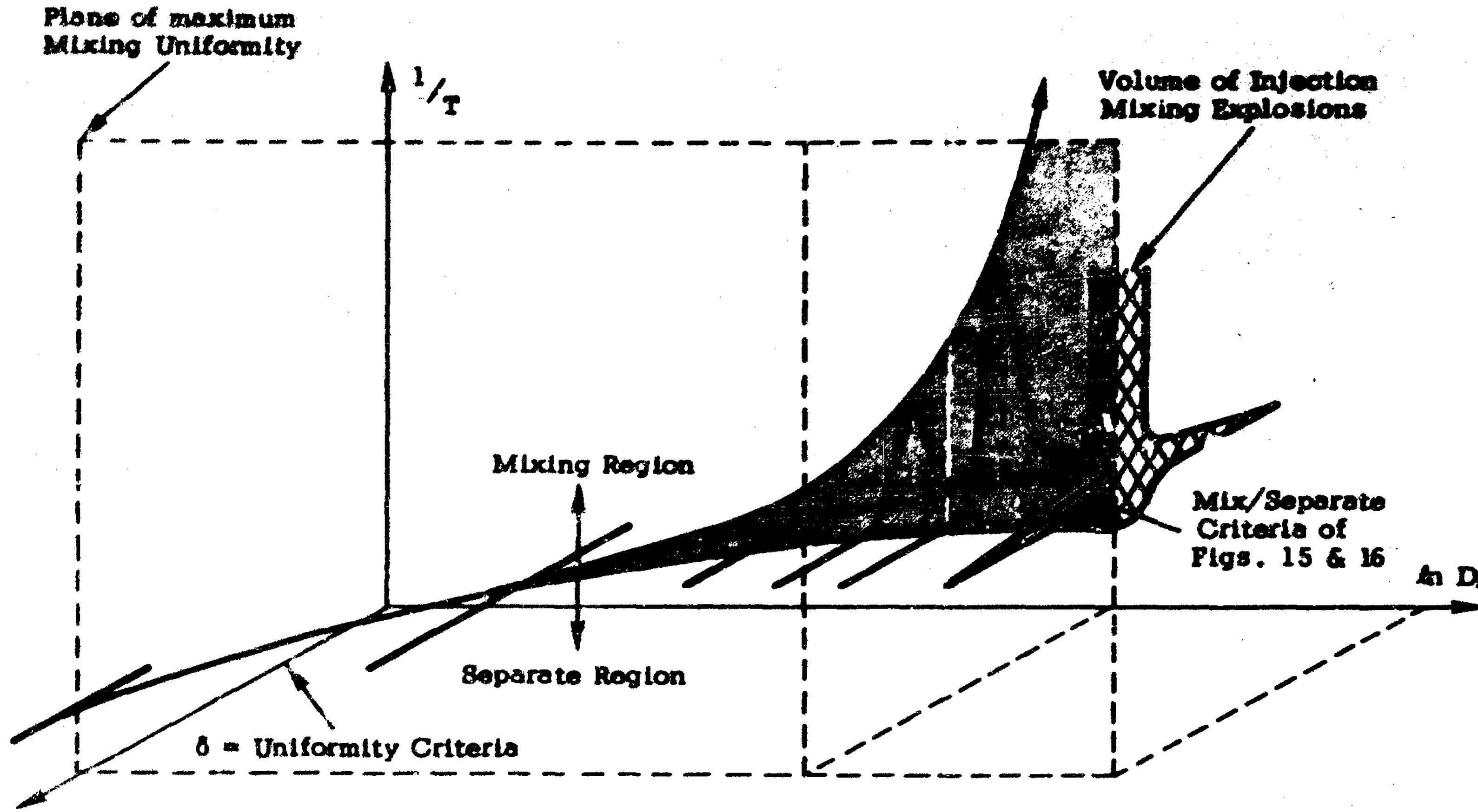


Figure 4. Apparent Effect of Uniformity Criteria on the Volume of Injection Mixing Explosions.

3. EXPERIMENTAL APPARATUS

a. Experimental Technique

The experimental technique is based on photographic observation of the impingement region of a pair of rectangular jets. Injector plates of different orifice sizes and impingement angles are used. Various injector plates are shown in Figure 5. A pyrex or calcium fluoride window which extends beyond the impingement point, covers the front face of the injector plate. This allows photographic observations of the impinging streams flowing over the window and at the same time still retains the basic feature of a set of three dimensional impinging jets. Liquid interface of the impinging fuel and oxidizer streams can be distinctly observed. This technique allows liquid interface of the impinging streams to be clearly observed as compared with the impingement of two free streams. Mixing and separation phenomena are identified and defined based on these photographic results.

b. Impingement Model

The stainless steel impingement test model is shown in Figure 6. The injector support and the orifice plate are fitted into a chamber block. The chamber is open along its whole length on one side. A lucite window with pyrex or calcium fluoride inserts is mounted on the open side of the chamber. This allows photographic observation of the impingement region. A nozzle is attached to the bottom of the chamber block. Chamber pressures of 500 psi can be easily attained by varying the nozzle sizes. A schematic of the chamber block and the injector support is shown in Figure 7. The support is designed for a triplet as well as a doublet injector plate. The propellants are temperature controlled up to the injector plate by means of coaxial lines.

c. Flow System

A schematic of the nitrogen tetroxide/hydrazine flow system is shown in Figure 8. The flow systems are fabricated with 304 stainless steel lines. The propellant tanks are designed for a working pressure of 1000 psi. The tank capacities are approximately 1/3 gallon. Pressurization of the tanks is controlled by a Grove regulator and a release valve which is set at 1000 psi. Two solenoid valves are used to vary the dome pressure of the regulator. The dome pressure is always set at approximately 950 psi. Propellant flow rates are controlled by variable area cavitating venturies and are metered by turbine type flow meters. The flow controllers are micrometer head type. This device provides easy and precise control of the propellant flows and allows for more efficient testing with the ability to match desired stream momentum ratios. The propellant tanks and lines are provided with heat exchangers. Propellant temperature is controlled by flowing coolant at the desired temperature through the heat exchangers. The coolant temperature is regulated with a refrigeration unit with heat exchangers on the condenser and evaporator. Coolant temperature is controlled by throttling the flows through the condenser and evaporator heat exchangers. The propellants are first led to flow to the exhaust tank. When the desired temperature is achieved, the propellant is introduced into the impingement block. Pressurization of the exhaust tank is achieved by a two stage regulator. This enables recovery of the propellants from the exhaust tank.

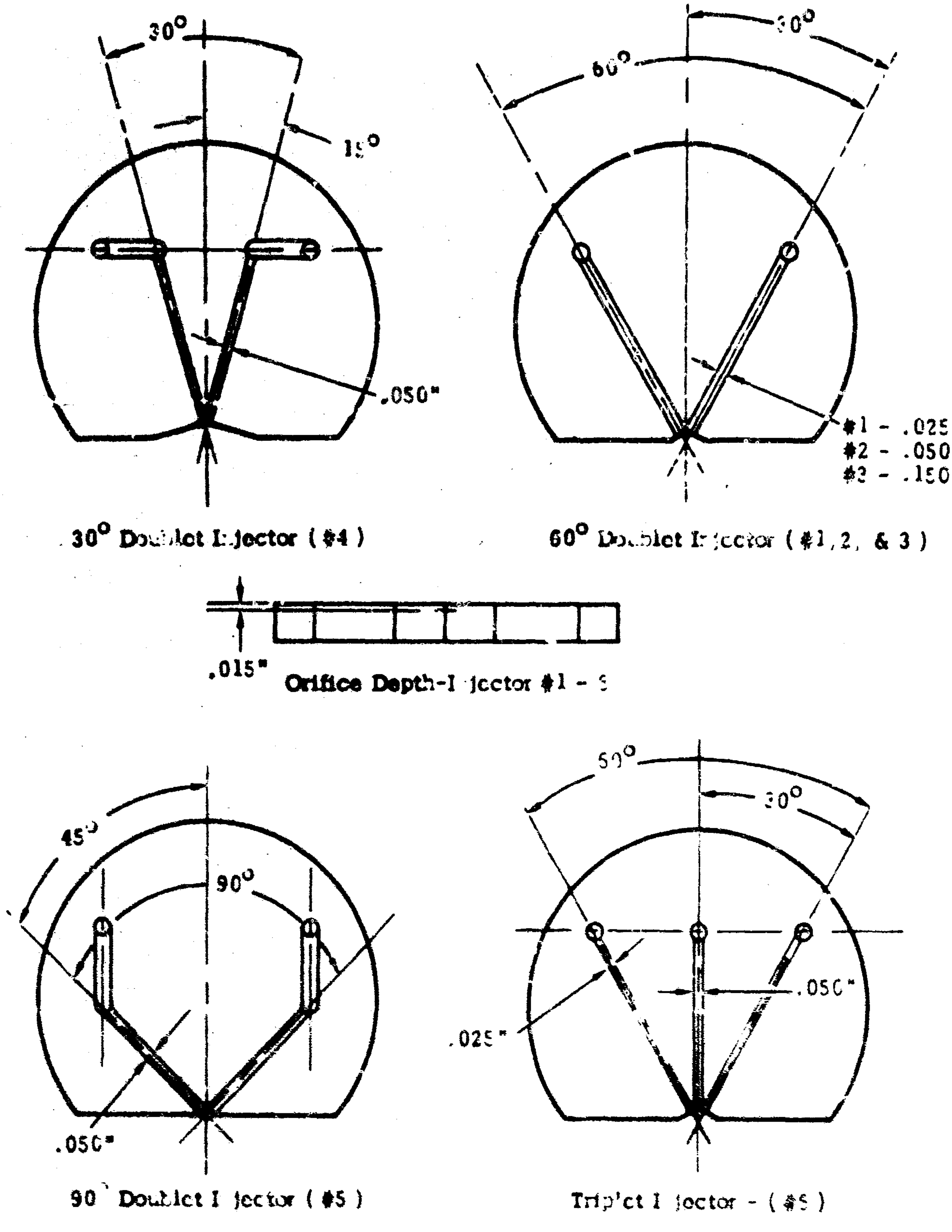


Figure 5. Injector Plates

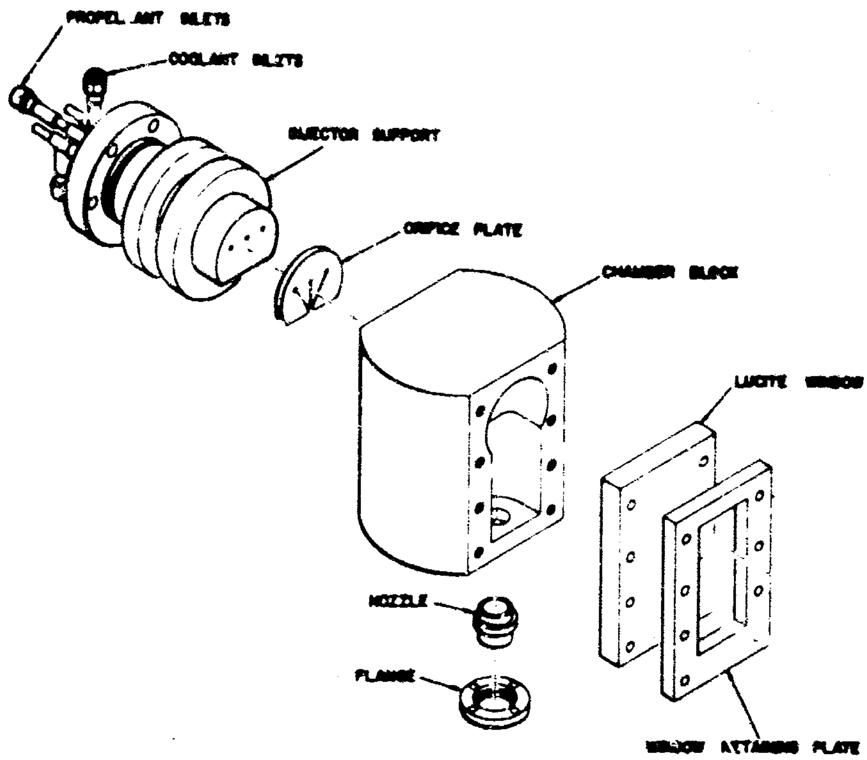


Figure 6. Impinging Stream Test Model.

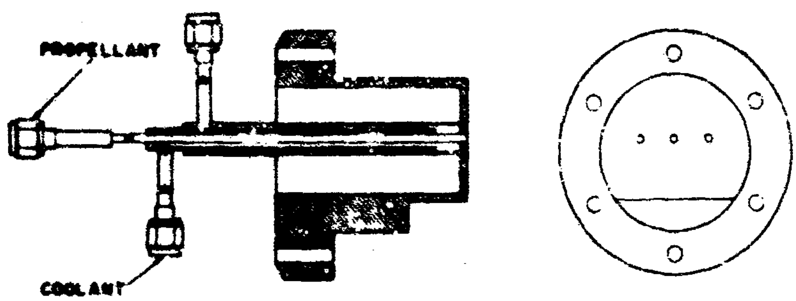


Figure 7a. Injector Mounting Support for Hot Firing

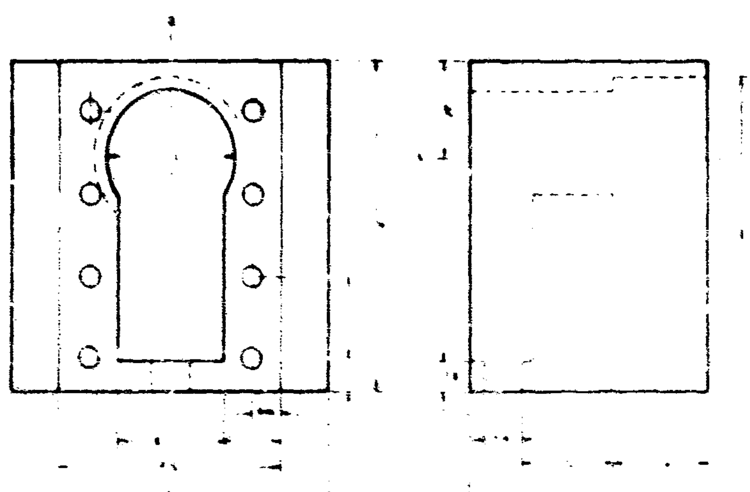


Figure 7b. Impinging Block for Hot Firing

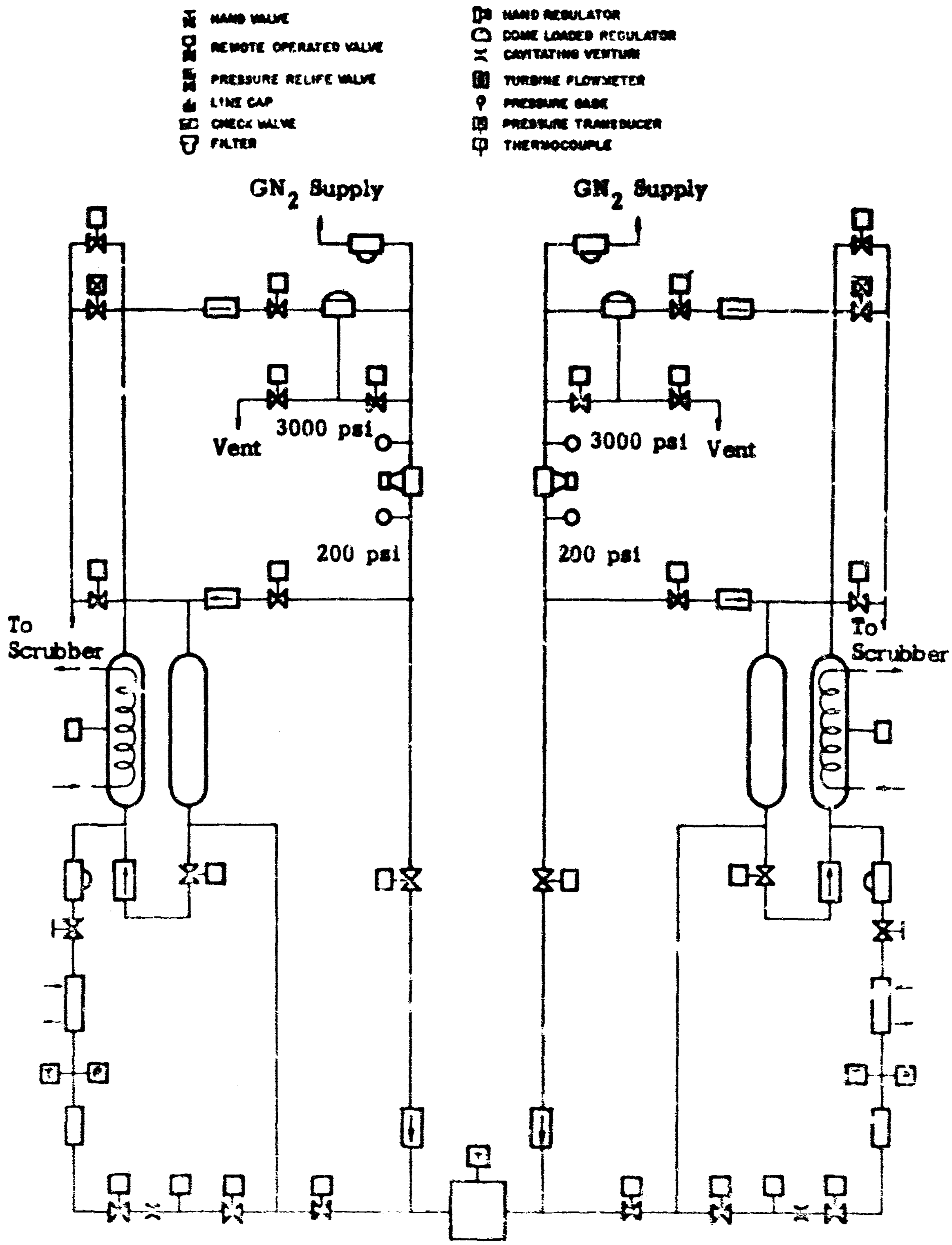


Figure 8. N_2O_4/N_2H_4 Flow System.

A separate flow system is used to provide liquid compound A to the impingement apparatus. The schematic of the liquid compound A supply system is shown in Figure 9. The system is designed for a working pressure of 1000 psi. Compound A temperature can be easily varied from -300°F to 120°F. All the nitrogen refrigerant and purging gas is provided by an 800 gallon liquid nitrogen storage dewar maintained at 40 psi, and located adjacent to the test area. This supports the test setup with extremely dry nitrogen gas for the various purging cycles and cold liquid and gas nitrogen to provide low temperature conditioning. Propellant temperatures above ambient conditions is achieved by heating the nitrogen gas. Compound A is stored in cylinders and transferred to the run tank, as required, during the test program. Pressurization of the run tank is achieved with helium gas. To insure the moisture content of the helium gas is within acceptable limits, all helium used for propellant pressurization is passed through a liquid nitrogen refrigerated molecular sieve dryer.

The vent gas of the flow system is neutralized with a charcoal reactor before being exhausted into the atmosphere. Combustion products from the test chamber are aspirated with nitrogen gas, scrubbed with water, and periodically neutralized in the disposal ponds.

The flow system is being operated remotely during test runs. Various solenoid valves and pneumatic controlled ball valves are used for the hydrazine and nitrogen tetroxide supply systems. Pneumatic controlled Nupro bellow valves are used for the compound A system.

Pressure is measured by strain gauge transducers. The strain gauge is powered by a six-volt power supply. The transducer output is fed through the patch panel into an amplifier to the oscillograph galvanometer. The strain gauge system is provided with a zero balance circuit and an electrical calibration unit which is put into the circuit through a selector switch. The pressure transducers have a natural frequency of 8000 CPS and a linearity of $\pm$ 0.5%. The transducers are calibrated with nitrogen gas using a high accuracy Bourdan gage. The Bourdan gage is calibrated to an NBS standard and is accurate to $\pm$ 0.25%.

Hydrazine and nitrogen tetroxide flow rates are measured with Cox turbine type flow meters. Compound A flow rates are measured with two Potter flow meters. The flow meter output signals are fed into an amplifier to the oscillograph. The flow rate is determined from the meter frequency output and the propellant density.

Propellant temperatures are measured with I/C thermocouples. The thermocouple output is fed through the patch board into an amplifier to the oscillograph.

The impingement test stand with compound A supply system is shown in Figure 10a. A close view of the test stand is shown in Figure 10b.

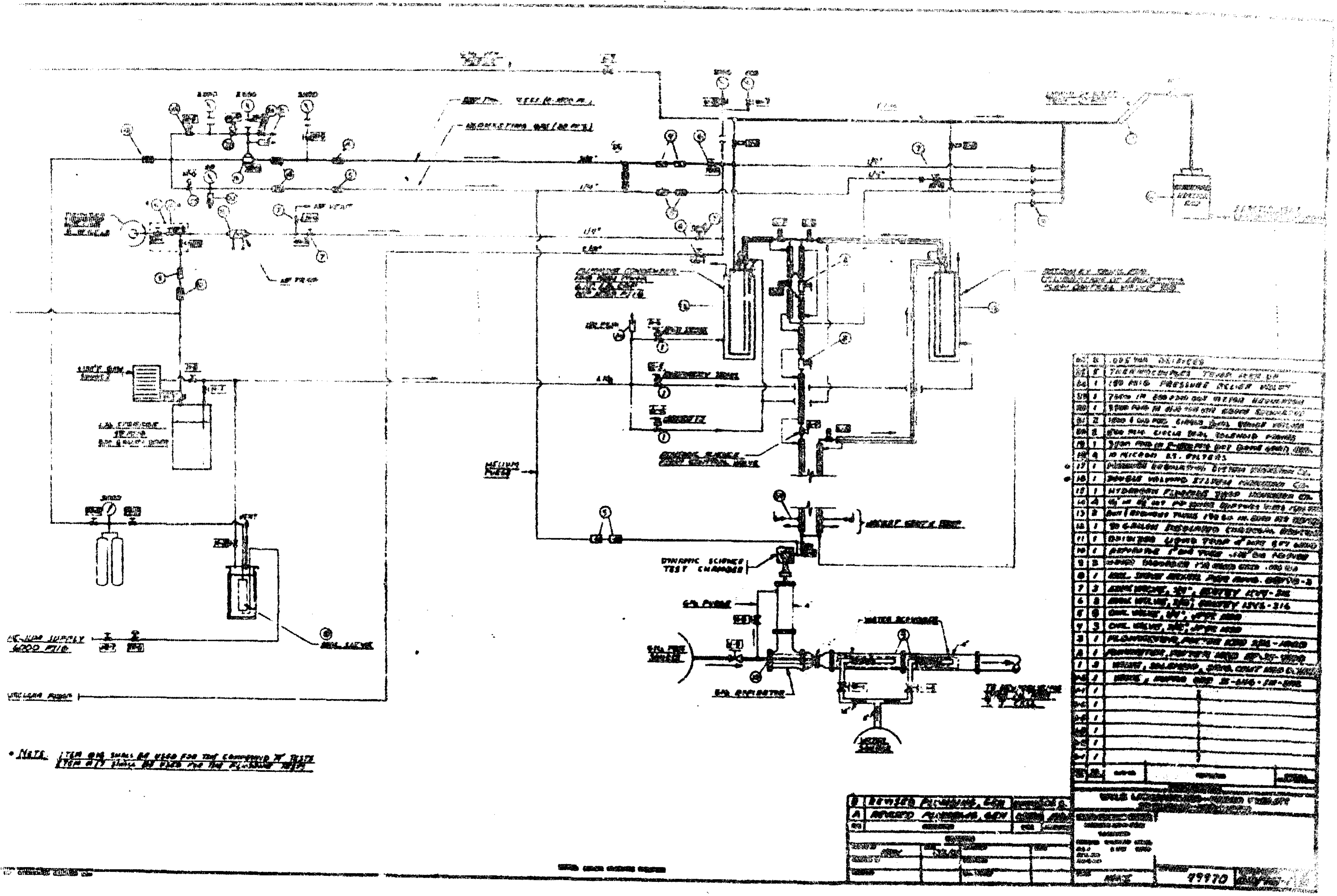


Figure 9. ClF_5 Supply System.

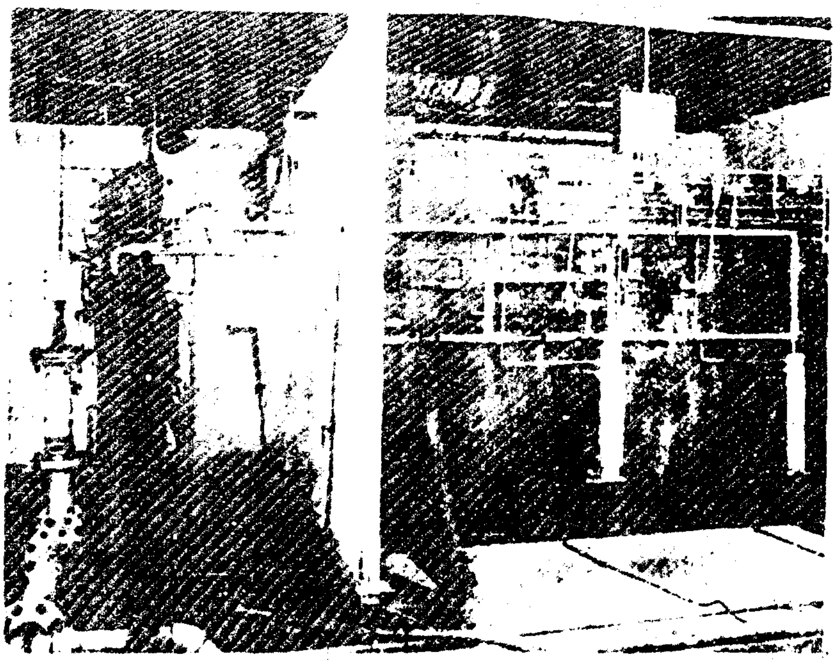


Figure 10a. Test Stand with Compound A Supply System.

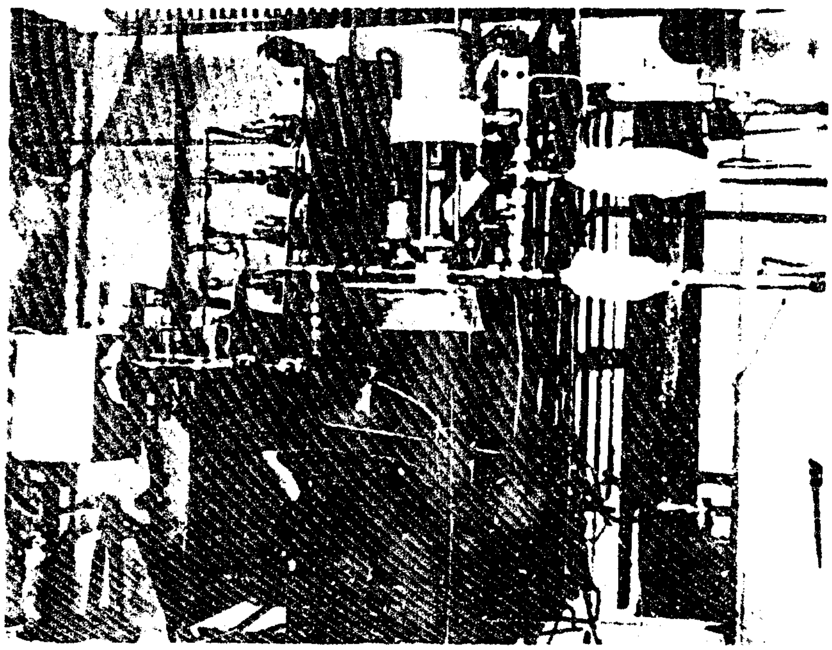


Figure 10b. Close View of Impingement Test Stand.

d. <u>Control Console</u>

The test control console houses the facility and propellant control panel, a test sequence unit, amplifier, and recording oscillograph with related components. The console is shown in Figure 11 The instrumentation system is centered around a Midwestern 801 recording oscillograph. Propellant temperatures at the injector plates, propellant flow rates and the chamber pressure are recorded on the oscillograph. Propellant tank pressures are recorded on a two channel strip recorder. Propellant temperatures downstream of cavitating venturies, tank temperatures, and flow meter temperatures are recorded on a multipoint recorder.

e. <u>Photography</u>

The impingement region is photographed using a Graphex 4x5 still camera. A Written No. 34 filter is used to mask out the flame light. This filter transmits only in the blue and red region. Poloroid color film is used with a carbon arc lamp and photoflood front lighting techniques.

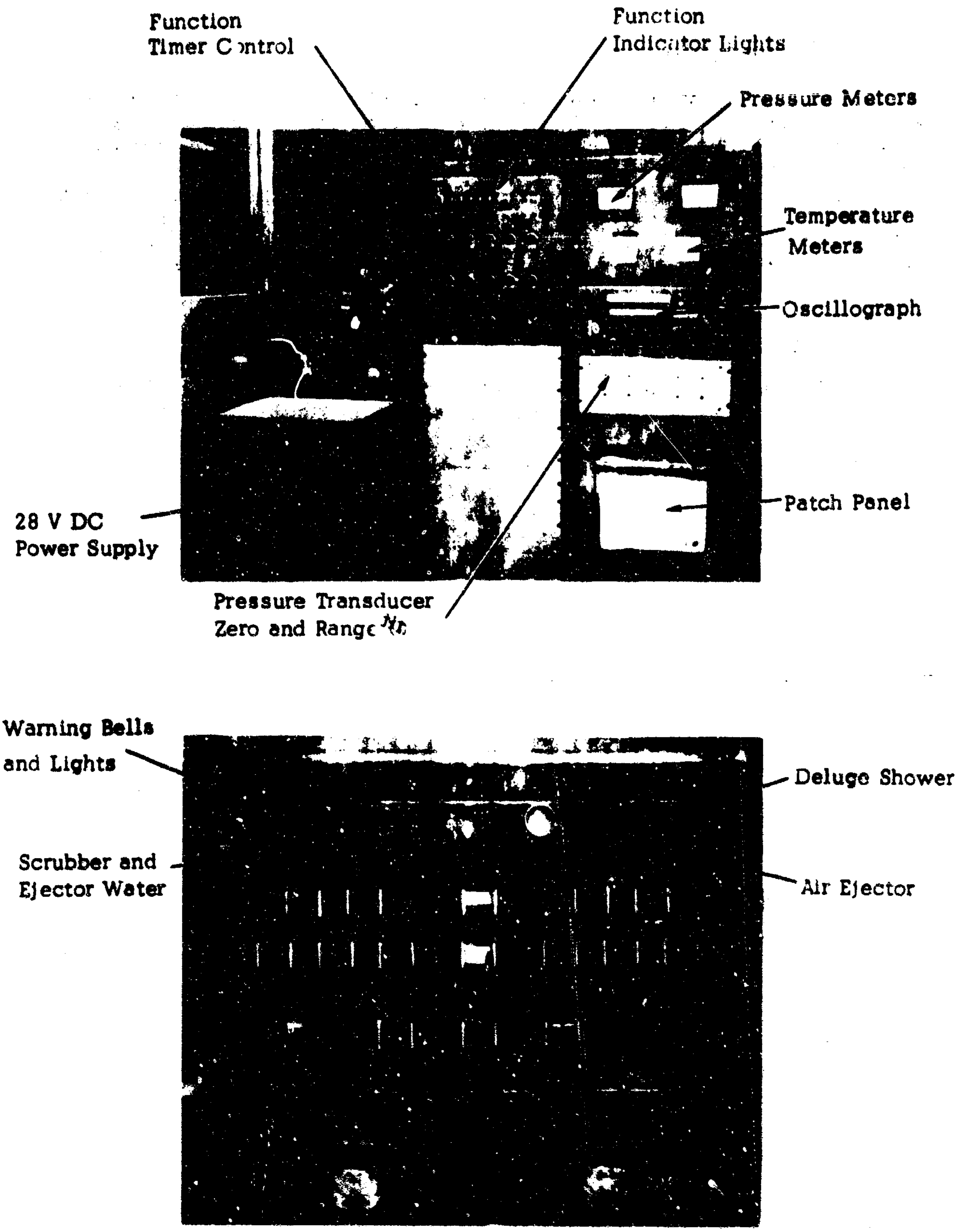


Figure 11. Control Console with Facility Control Panel.

4. IMPINGEMENT OF NITROGEN TETROXIDE/HYDRAZINE FAMILY PROPELLANT SYSTEMS.

a. Experimental Data

Impingement experiments were conducted by impinging streams of hydrazine, monomethyl-hydrazine and mixtures of hydrazine and unsymmetric-di-methyl hydrazine (A-50) with nitrogen tetroxide. Propellant temperatures were varied from 40°F to 120°F. The characteristic mixing time, D/V was varied from 0.2×10^{-4} seconds to 3×10^{-4} seconds. To evaluate the effect of pressure, chamber pressure is varied between 15 psi to 500 psi.

Figures 12, 13, and 14 are photographs of impingement region of hydrazine family fuels with nitrogen tetroxide. A Wratten No. 34 filter is used to mask out the flame light. A dark purple region along the contact surface is present for monomethyl-hydrazine/nitrogen tetroxide impingement (Fig. 13a). This is most probably due to certain hydrocarbon intermediates.

Figure 15 is the impingement data for nitrogen tetroxide and hydrazine streams (Ref. 5) for both rectangular and circular jets. The data are presented in terms of the propellant temperature expressed as 1/T and the mixing time D/V. The experiments are conducted at the ambient pressure of ≈ 15 psi. The experimental data in terms of the inverse of the absolute propellant temperature and D/V agree very well with the relationship suggested in Equation (8). Figure 16 is nitrogen tetroxide/hydrazine impingement data for chamber pressures varying between 15 psi and 500 psi. The angle of impingement is generally 60. Impingement angles of 30° and 90° are also used occasionally. Chamber pressure does not seem to play any significant role with respect to stream separation phenomena. Figures 17 and 18 are impingement data for nitrogen tetroxide/monomethyl hydrazine and nitrogen tetroxide/aerozine 50 respectively. Separation limit for these propellants differs significantly from that of nitrogen tetroxide and hydrazine.

b. Discussion

The impingement model outlined in Section 2b relating the propellant temperature and the mixing time (Eqn. 8) allows good correlation with experimental data. Beyond this correlation the order of magnitude of the "overall activation energy" E, can be estimated based on the slope of the limiting curve. E assumes a value of approximately 20 kcal/mole of reactants. A more detailed calculation has been carried out by Jaye and Blauer (Ref. 14) for the data of Figure 15. By assuming that ignition occurs at 1% of the total reaction and using $\sin\theta/2=1/2$ for a 60° impingement, they calculated that E and log A are respectively 24 ± 3 kcal/mole and 15.7 ± 0.5 cc/mole/sec.

As observed by Jaye and Blauer, rate constants obtained from the impingement results are in excellent agreement with the work of Sawyer and Glassman, (Ref. 15). They obtained $E = 26.7 \pm 1.1$ kcal/mole and $\log A = 15.8 \pm 0.6$ cc/mole/sec for the gas phase ignition process. Jaye and Blauer continue that this agreement leads "to the conclusion that either the rate controlling process (of stream separation) occurs in the gas phase or the reaction mechanism is the same in both the liquid and gas phases." This very interesting observation is supported by consideration of surface physics. When two liquid surfaces are in contact, the surface layer molecules which contact the opposite surface would tend to follow

Figure 12a. Stream Doublet Separation (N_2H_4/N_2O_4).

Figure 12b. Stream Doublet Mixing (N_2H_4/N_2O_4).

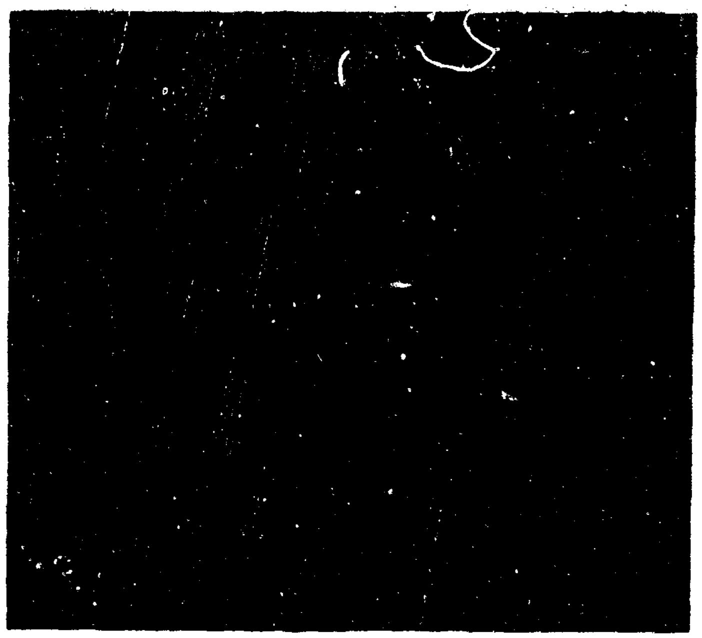


Figure 13a. Stream Doublet Separation (MMH/N_2O_4).

Figure 13b. Stream Doublet Mixing (MMH/N_2O_4).

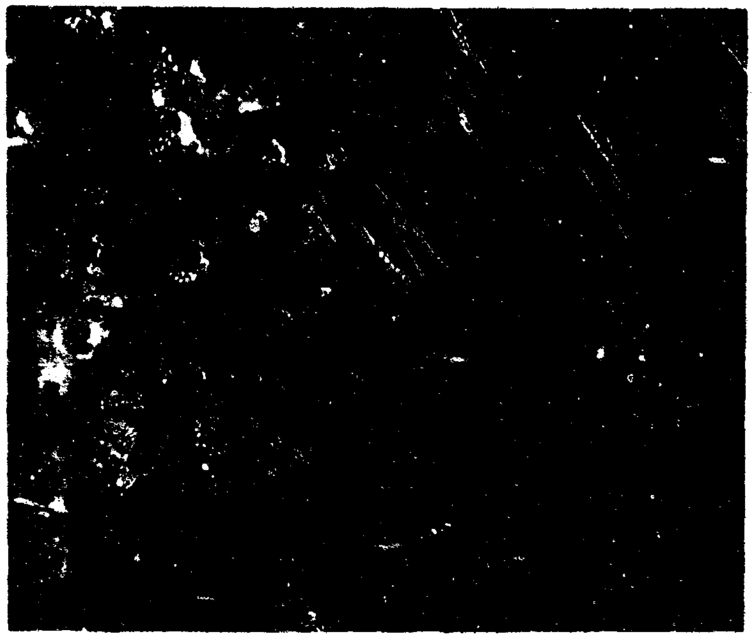


Figure 14a. Stream Doublet Separation (A-50/N_2O_4).

Figure 14b. Stream Doublet Mixing (A-50/N_2O_4).

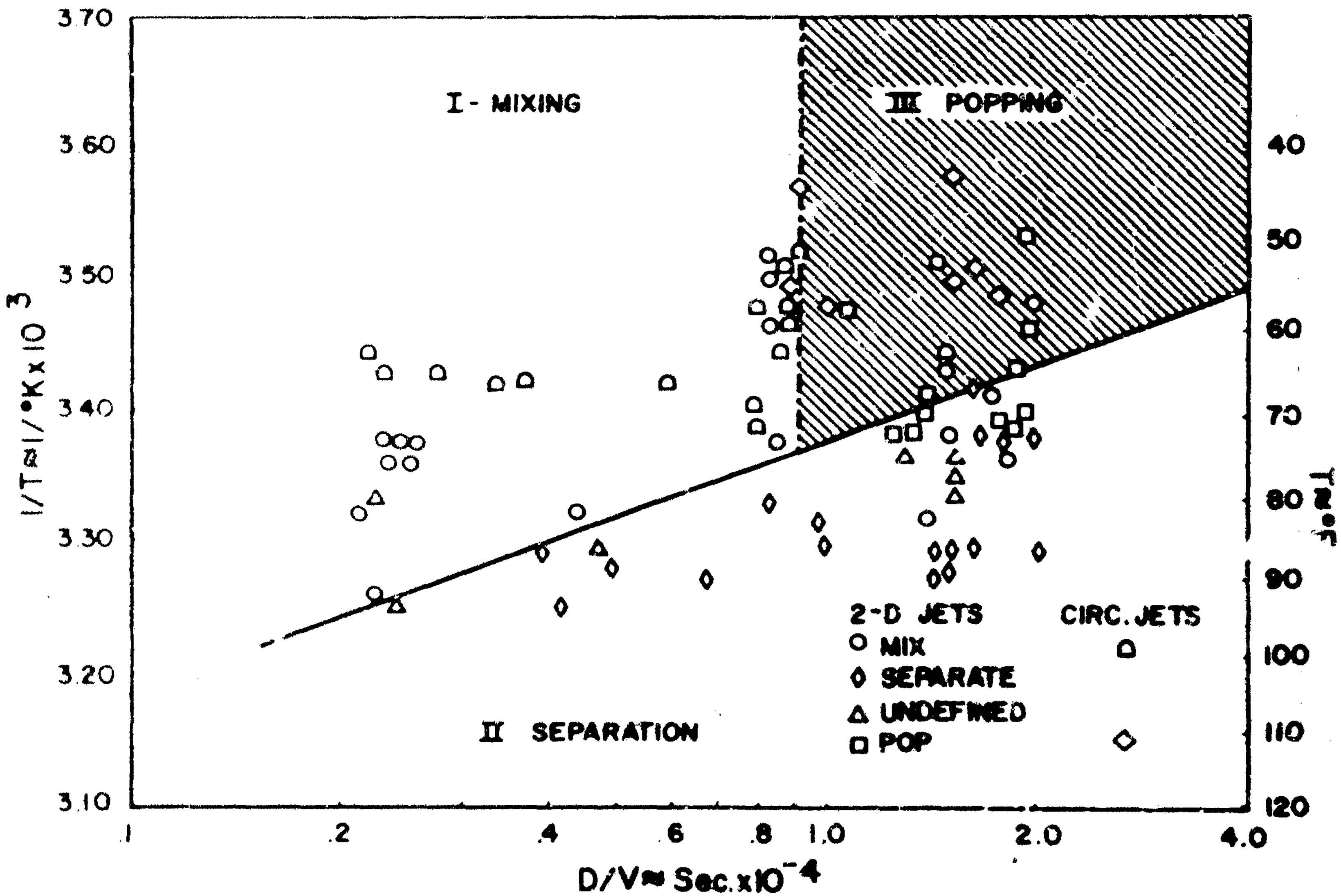


Figure 15. Jet Separation Data fo· N_2O_4/N_2H_4 System.

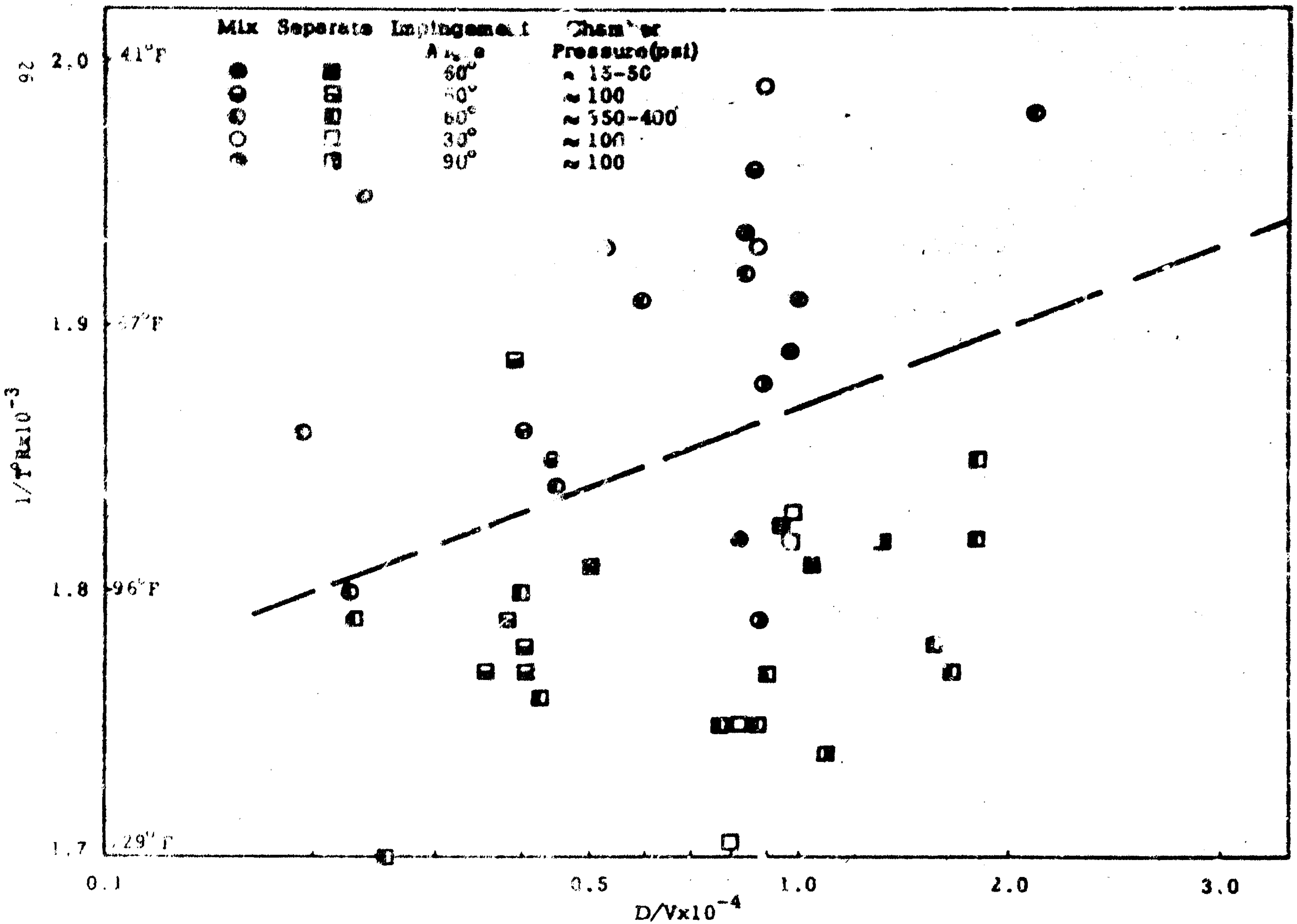


Figure 16. Separation Data for N_2O_4/N_2H_4 System for Different Chamber Pressures.

vapor pressure kinetics rather than fully mixed liquid phase kinetics. This model is supported by motion pictures of Weiss, Fisher, Gerstein, and Johnson (Ref. 16) through which they observed that nitrogen tetroxide drops appeared to be immissible in hydrazine and maintained their original surface identify.

The data presented in Figure 16 definitely indicate that stream separation does not depend on the chamber pressure. When a locally strong exothermic reaction takes place between the propellants to liberate sufficient gas products and heat to vaporize the propellants and the reaction intermediates so as to blow the stream apart, chamber pressure only plays a secondary role of increasing the boiling point of the liquid. Since the latent heat is the dominating factor, the effect of chamber pressure does not play a significant role. To further illustrate this point, the boiling point of N_2O_4 at 15 psi and 500 psi are 530^oR and 700^oR respectively. The latent heat of vaporization within these temperature ranges are approximately 400 Btu/lb and the specific heat C_p is approximately 0.3 Btu/lb^oR. The significance of pressure can be evaluated by the ratio:

$$\frac{C_p[T_b(500\ \text{psi}) - T_b(15\ \text{psi})]}{\text{latent heat}} = \frac{0.3(170)}{400} \approx 12\%$$

This indicates that a 500 psi pressure increase only causes a first order effect on the separate/mix temperature criteria. When the order of magnitude of the ratio of the sensible heat difference to the combustion heat available is compared, the amount of heat used in reaching different boiling points is even less significant.

Preliminary tests on nitrogen tetroxide/aerozine 50 and nitrogen tetroxide/monomethyl-hydrazine systems have been carried out. Separation limits of these propellant systems are to be compared with that of nitrogen tetroxide/hydrazine systems. For a given mixing time D/V, separation limits of these propellant systems occur at a higher temperature than that of hydrazine. This indicates that the nitrogen tetroxide/hydrazine is a more reactive propellant system as compared with that of nitrogen tetroxide/monomethyl-hydrazine and nitrogen tetroxide/aerozine 50 systems. Based on jet separation phenomena, at a given temperature and mixing time, aerozine 50 and monomethyl-hydrazine with tetroxide will more readily mix and therefore give a more intense initial combustion zone than the hydrazine with nitrogen tetroxide. However in each case the separation temperature may be reached, depending upon the use of regenerative cooling and resulting injection temperature.

c. Engine Design Application

Stream separation influences the engine performance in many respects. When reactive streams are blown apart the result can be a high degree of flow striation. This leads to poor combustion efficiency. When separation occurs maximum striation and efficiency loss is associated with a single element injector. The striation effect upon efficiency losses would diminish for larger numbers of injector elements. This effect was established experimentally, (Ref. 17), and indicated that the combustion efficiency loss for a single element, four on one, injector is roughly twice that of a ten element injector.

The influence of nonuniform mixture ratio distribution, which can be induced by stream blow apart, has been theoretically calculated based on a

stratified supersonic nozzle flow field (Ref. 18) and internally, based on non-uniform vaporization streamtubes (Ref. 19). Various prescribed oxidizer to fuel ratio profiles have been used to evaluate their effect on performance. Nitrogen tetroxide/aerozine 50 and fluorine/hydrogen systems generally indicated losses from 1.0 to 4.0% in specific impulse. Liquid oxygen/hydrocarbon (LOX/RP-1) system exhibited a specific impulse loss of approximately 8%.

The mix/separate criteria presented in this report also point out the importance of proper injector design upon thrust chamber liner compatibility. Proper injector design must include the influence of propellant temperature upon whether or not the fuel-rich stream separates and remains next to the liner; or in the low temperature case (mixing) forms an intense combustion zone. This effect will be found not only in the fuel-rich barrier zone but also in the intense stoichiometric combustion of the primary zone. If the primary injector zone is within the mixing regime it may actually blow through the fuel-rich combustion of the barrier zone. Thus liner compatibility is as strongly dependent upon propellant temperature as it is upon propellant distribution.

It has been shown in the previous section that by properly controlling the propellant temperature, propellant injection velocity and orifice size, regimes of mix/separate phenomena can be defined. This knowledge can be used to great advantage by design engineers. Based on data similar to those presented in Figures 15 to 18, characteristic parameters such as propellant temperature and mixing time, D/V can be defined in order to achieve proper combustion mixing leading to better engine performance, stability, and compatibility. Particularly when anomalous engine behavior is observed, attention should be paid to the operating region of mix or separate mechanisms, at the very least this work points out the importance of controlling and monitoring propellant temperature during engine firing test programs.

Engine instability is another problem which is sometimes directly attributed to separation phenomena. High pressure transients have often been observed at chamber wall pressure transducer stations during full-scale engine development and test programs (Refs. 3 and 9). These transients are rather arbitrarily termed "pops," depending upon amplitude and frequency. However, their initiation source is the subject of much speculation. During the course of this impingement research and in previous impingement experiments conducted at NASA/Lewis (Ref. 13) and at Dynamic Science (Ref. 12), it was found that injection mixing explosions often occurred reproducibly in the lower temperature (mix) regime, at long residence time. Their occurrence also appears to increase under these conditions when the streams have a high degree of mixing as shown in Figure 4, (i.e. δ defined on page 7 to be approximately 0.5 or that the streams have approximately equal momentum or stagnation pressures.)

High speed motion picture cameras have been used to record the explosion of the impingement region (Ref. 12). This explosion phenomena is very detrimental to stable engine operation because they can serve as triggering source for spray detonation as shown in Figure 3. This detonation wave at the impingement zone also causes injector flow irregularities with apparent "flow shutoff" of a few milliseconds resulting in rough engine operation. The pictures on Figure 3 were obtained with long interfacial residence time and substantial liquid mixing throughout the impingement region. Unlike the separation phenomena which are caused by a

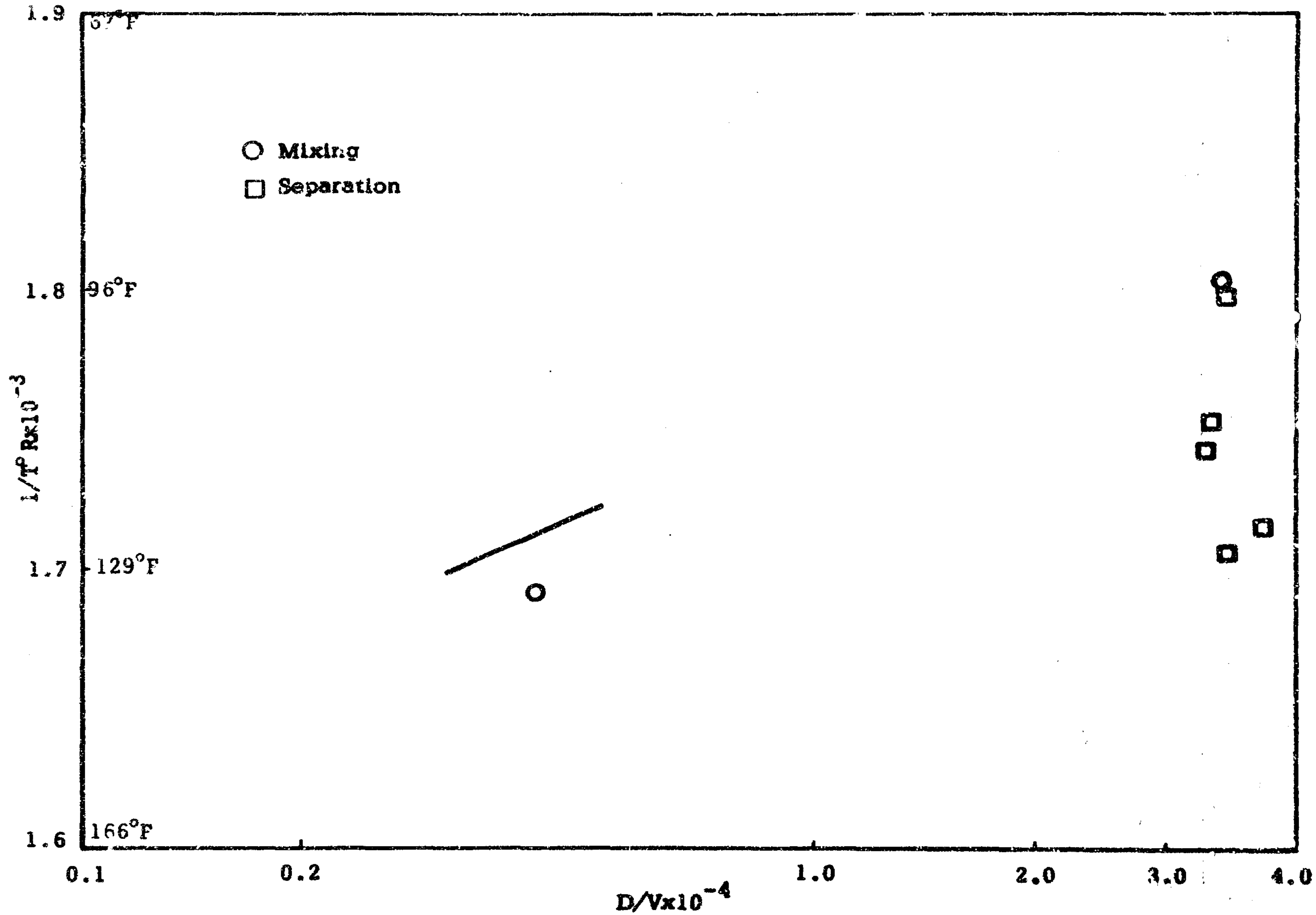


Figure 17. Separation Data for N_2O_4/ [illegible] System.

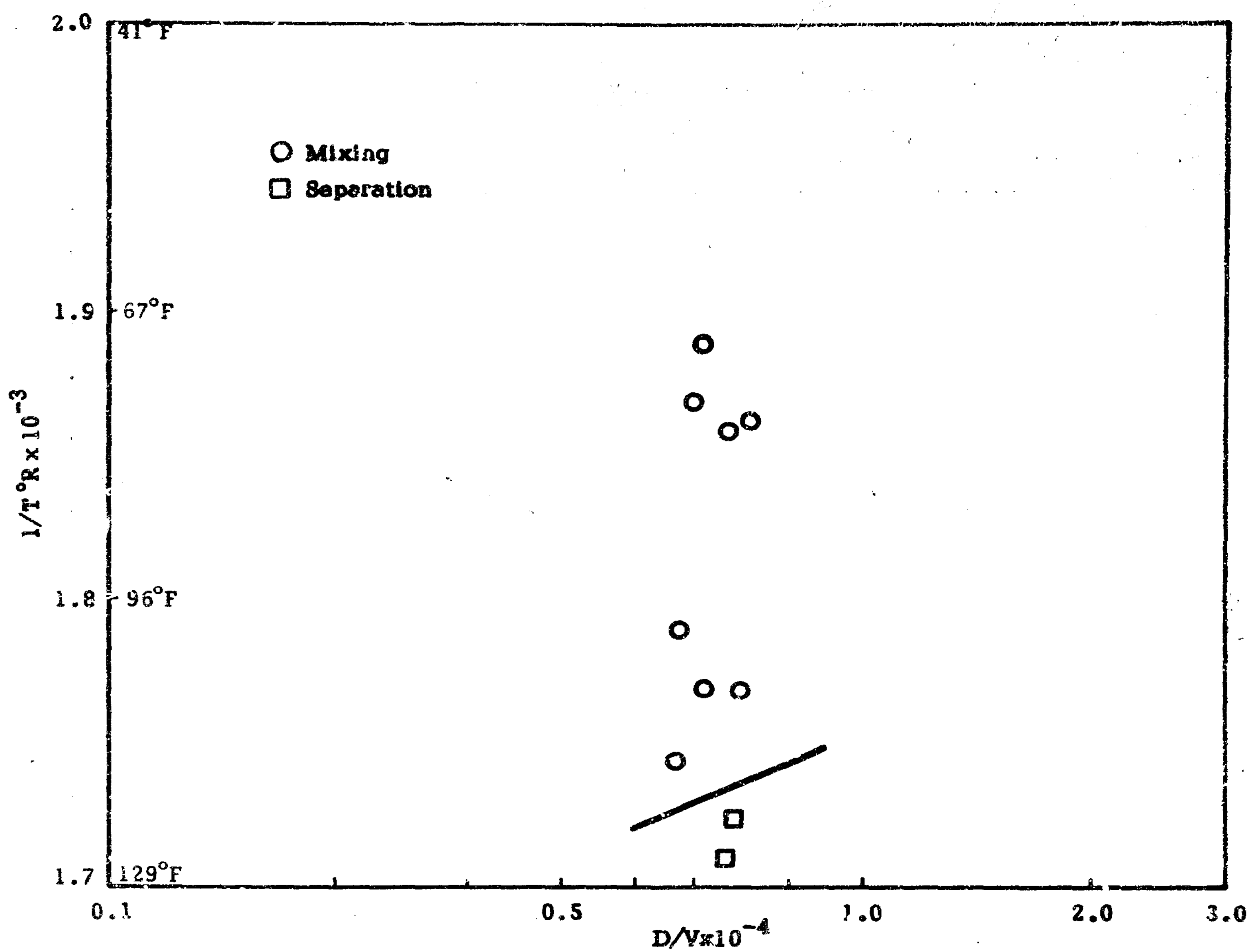


Figure 18. Separation Data for N_2O_4/A-50 System.

locally exothermic reaction, the reaction within the entire impingement region results in spray detonation. For smooth engine operation the design engineer has to avoid these conditions which lead to detonation waves. The occurrence of these explosions will be unavoidable with unlike hypergolic propellant injection unless care is taken to insure that each set of elements within the injector are operating within the same regime. Because of manifold laycut and L/D orifice problems this is often impossible but it should always be a major consideration for the removal of "pops" and roughness. If each set of elements are different there may be a random set sometimes passing through the injector mixing explosion regime. The use of a single element system such as a center flow injection scheme overcomes the element randomness.

5. COMPOUND A IMPINGEMENT WITH HYDRAZINE

a. Experimental Difficulties

The impingement model (Fig. 6) for nitrogen tetroxide/hydrazine tests is also used to study the jet separation of compound A and hydrazine. A separate flow system (Figs. 7 and 8a) is used for delivering compound A. Propellant is temperature regulated up to the injector plate (Figure 7a), since heat transfer between the plate which is initially at ambient temperatures and compound A which is close of 0°F only increases the propellant temperature by a fraction of a degree.

Impinging compound A with hydrazine presents many additional difficulties. Compound A is a more reactive and corrosive propellant as compared with nitrogen tetroxide. This often causes substantial damage to the viewing window of the impingement test model. Lucite is certainly not compatible with compound A and this is evidenced with the initial runs using lucite windows. Reactions between lucite and compound A upstream of the impingement point is shown in Figure 19. The bright flame along the entire length of the compound A nozzle is the reaction of compound A with lucite. This in turn caused substantial damage to the injector plate as shown in Figure 20. To partly remedy this problem, the injector plate is modified as shown in Figure 21. This also allows impingement to take place away from the window. Lucite with pyrex or calcium fluoride inserts are used for window materials. Damages on these windows are very often too severe to obtain quality photographs. The chamber window following a compound A/hydrazine impingement reaction is shown in Figure 22. It is a lucite window with a pyrex insert 1/4 inch thick. In addition to the severe burning of the window by compound A, much damage is caused by the thermal stresses resulting from the strong exothermic reactions at the impingement region. A typical photograph using calcium fluoride insert is shown in Figure 23. By closely investigating the calcium fluoride insert following the impingement test, damage was found to be mainly caused by thermal stresses since the window is 3/8 inch thick. It appears that calcium fluoride is compatible with the compound A at these high temperatures. Better quality photographs might be obtained with thin calcium fluoride inserts.

The vent gas of the flow system is neutralized with a charcoal reactor before vented into the atmosphere. Refractory cement is used as a heat insulator for the charcoal scrubber. The strong exothermic reaction between compound A and charcoal sometimes "melts" this cement insulator which is shown in Figure 24.

b. Results

A photograph of impinging streams of hydrazine and compound A is shown in Figure 25. The fuel and oxidizer flow rates are 0.022 lb/sec and 0.0343 lb/sec. The initial temperatures are 56°F and 0°F. Based on photographs of the impingement region, mix/separate phenomena is less distinct as compared with nitrogen tetroxide and hydrazine. Unlike nitrogen tetroxide which is brown colored Compound A is colorless.

Approximately fifty impingement tests using hydrazine and compound A have

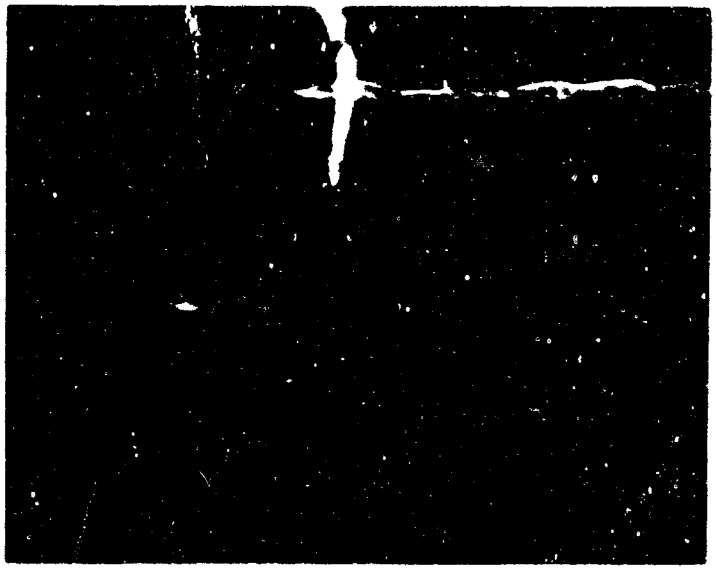


Figure 19. Reaction of Lucite Window in Compound A Stream.

Figure 20. Injector Plate Following Compound A/N_2H_4 Reaction.

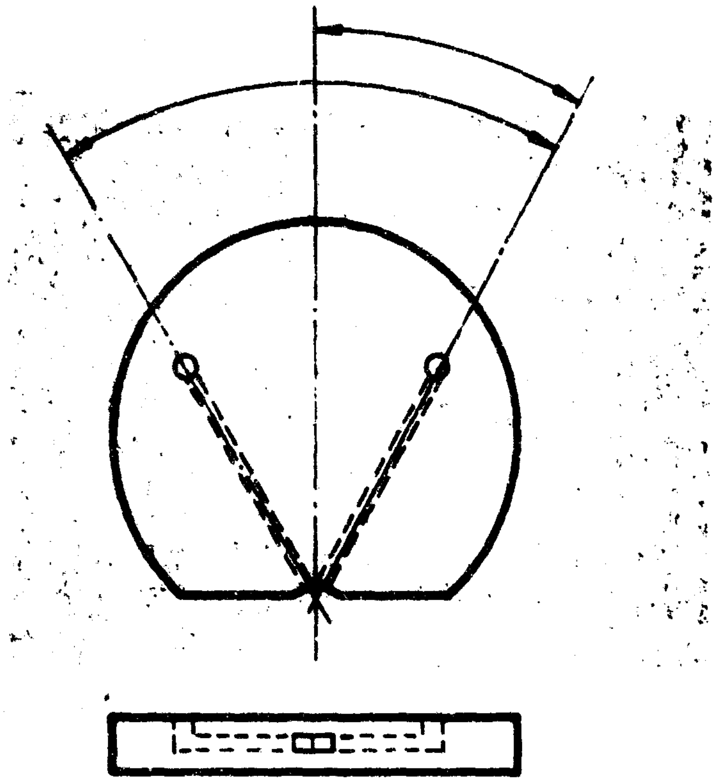


Figure 21. Modified Injector Plate for Compound A Propellant.

Figure 22. Lucite Chamber Window with Pyrex Insert following Compound A/Hydrazine Reaction.

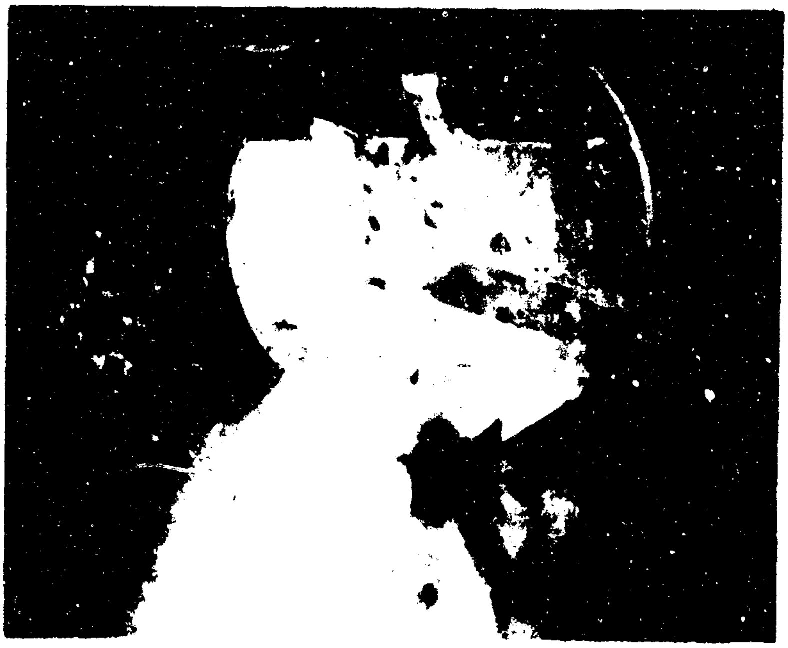


Figure 23. Lucite Window with Calcium Fluoride Insert.

Figure 24. Melted Refractory Cement of Charcoat Scrubber.

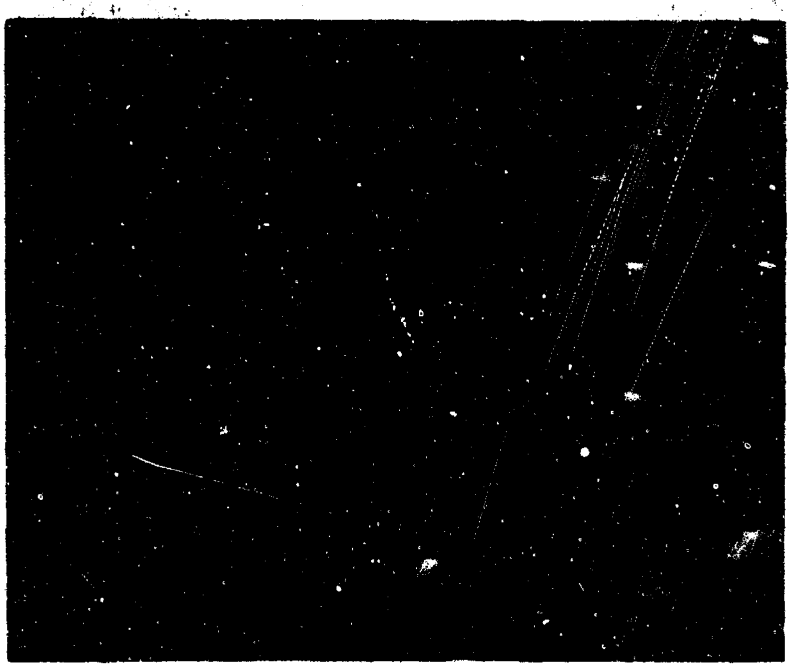


Figure 25. Hydrazine/Compound A Impingement. (Compound A, Left Injector Hydrazine, Right Injector).

been carried out. The chamber pressure was varied from 15 psia to over 100 psia. Hydrazine and Compound A temperatures ranged from 40°F to 60°F and 0°F to 30°F respectively. The mixing time, D/V was within 0.2×10^{-4} sec to 2×10^{-4} sec. Within these temperature and velocity ranges, it appeared that impingement of compound A and hydrazine always resulted in separation.

The separation phenomena are partly attributed to the high vapor pressure of compound A. Its boiling temperature at atmospheric pressure is 7° F, while the hydrazine had to be maintained above 35° F to keep it from freezing. Thus the compound A would boil on contact with the hydrazine at pressures below 45 psia (corresponding to hydrazine temperature of 60°F). Under such circumstances chamber pressure is indeed important to, first of all, assure liquid-liquid contact. The significance of chamber pressure in this case is not contradictory to the data of Figure 16 which show no pressure effect, but merely indicate that a boiling mechanism will cause separation up to the point where the chamber pressure allows liquid-liquid contact.

It is believed that better experimental results can be achieved with the viewing window further away from the impingement region. A lucite window with calcium fluoride inserts was compatible with compound A at the elevated temperatures. In the present experiment, test periods are approximately two seconds. Reducing testing periods will minimize possible window damage. This can be achieved by improving the existing by-pass line in the flow system so as to reduce the transient effects. Possibility of coloring one of the propellants can be investigated so as to obtain better photographs.

6. CONCLUSION

Based on experimental results of hypergolic propellant impingement studies, mixing or separation phenomena are usually observed. Corresponding to the first Damkohler number, a nondimensionalized number $\mathcal{D} = \tau_{chm}/\tau_{mix}$ can be defined. τ_{chm} and τ_{mix} are characteristic chemical reaction time and mixing time. Separation limit is defined by assuming $\mathcal{D} = 1$.

Impinging nitrogen tetroxide with hydrazine family fuels, the separation limit $\mathcal{D} = 1$ agrees very well with the experiment. Chamber pressures were varied from 15 psi to 500 psi. The predicted pressure effects (Ref. 6) were not observed. In fact, in the regime that was investigated, stream separation is independent of pressure. This is anticipated when chemical kinetics are governed by the rate of liquid phase reaction. Separation limits are observed at higher temperatures for A-50/N_2O_4 and MMH/N_2O_4 as compared with N_2H_4/N_2O_4 system indicating N_2H_4/N_2O_4 is a more reactive system.

It appears that stream separation always occurs by impinging Compound A and hydrazine with oxidizer and fuel temperatures varying between 0° F to 30° F and 40°F to 60°F respectively. Better experimental results can be obtained by reducing the testing period and using lucite windows with thin calcium fluoride inserts.

PART II

EXTENSION OF STEADY-STATE COMBUSTION MODEL

1. INTRODUCTION

The Dynamic Science steady-state combustion computer program has been in use at several installations for a number of years. It has been shown by many investigators to be a useful tool to investigate the performance and stability of liquid rocket engines. The program provides the linkage between propellant, engine, and injector parameters, and the performance of the system and guides the designer/analyst in making changes necessary to correct system deficiencies

This section describes a project performed jointly by personnel of the AFRPL and Dynamic Science under the direction of Capt. Charles J. Abbe to improve the operational versatility and economics of use of the steady-state combustion program.

2. PROGRAM DESCRIPTION

The basic model used in the Steady-State Combustion Program is an extension of the original work of Priem (Ref. 20). The model considers the conservation equations governing the heat, mass, and momentum transfer of a spray of liquid fuel drops traveling through a channel filled with oxidizer vapor. The assumption is made that propellant vaporization is the rate governing mechanism of the combustion process and that vaporization of the drop can be expressed by a Ranz and Marshall type correlation.

Dynamic Science extended this work (Refs. 21 and 22) to include the simultaneous vaporization of fuel and oxidizer sprays; thereby calculating vapor and liquid phase O/F along the chamber length. The thermophysical property calculations were also substantially improved. A valuable routine added to the program included the monopropellant burning effect of hydrazine type propellants and allowed calculated and measured combustion efficiencies to be correlated with these propellant systems (Ref. 23).

The program as listed in Reference 20 included all these effects but was still in an engineering development stage not entirely suited to production running. This work, in this computer extension phase, involved breaking the program up into subroutines of size suitable for manipulation, replacing the second order Runge-Kutta integration with a predictor-corrector type scheme, and improvement of program versatility. The bulk of the work was performed for the improvement of program versatility, i.e., generalizing the program to provide the capability of easily switching from one propellant combination to another. This involved segregating the property routines and generalizing their input, gathering the property data available and converting to the proper units

and specifying estimation procedures for properties not readily available. The majority of programming and all debugging were performed at the AFRPL computing facility.

The documentation cited here is only an attempt to provide a knowledge of the changes that have been made in the program. For a more complete description of the model and program, see References 19 and 20.

3. PHYSICAL PROPERTY ROUTINES

The following is a list of the physical property routines and units required by the program. The properties may be broken down into those of the fuel and oxidizer (both liquid and vapor) and those of the individual species comprising the combustion gas. The independent variable against which values are to be interpolated is also given. Oxidizer properties may be related in the program to the integer I = 1 and fuel properties by I = 2.

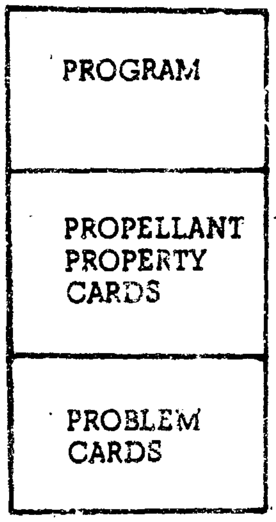
Fuel and Oxidizer Properties

Subroutines	Property (Units)	Independent Variable (Units)
PVAP	vapor pressure (psia)	liquid temperature (°R)
TBL	boiling temperature (°R)	pressure (psia)
RHØ	liquid density (lb/in³)	liquid temperature (°R)
VISCV	vapor viscosity (lb/in-sec)	temperature (°R)
CVAP	vapor specific heat (Btu/lb-°F)	temperature (°R)
FKA	vapor thermal conductivity (Btu/in-sec-°F)	temperature (°R)
CPL	liquid specific heat (Btu/lb-°F)	liquid temperature (°R)
ALM	heat of vaporization (Btu/lb)	liquid temperature (°R)

Combustion Species Properties

Subroutine	Property (Units)	Independent Variable (Units)
CØMP	combustion gas composition (mole fraction)	O/F ratio at different pressures (psia); maximum of 3 pressures
WTMINT	combustion gas molecular weight	O/F ratio at different pressures (psia); maximum of 3 pressures
TGINT	flame temperature ($^{\circ}R$)	O/F ratio at different pressures (psia); maximum of 3 pressures
VK3GAS	viscosity (lb/in-sec) for each species	temperature ($^{\circ}R$)
	specific heat (Btu/mole-$^{\circ}F$) for each species	temperature ($^{\circ}R$)
	(thermal conductivity calculated from μ and c_p)	
	molecular weight of each species	
DIFFU	calculates diffusion coefficient of fuel and oxidizer through combustion mixture	
	Lennard Jones Parameters	
	σ_1, atomic radius of oxidizer (Å)	
	σ_2, atomic radius of fuel (Å)	
	σ_j, atomic radius for each species (Å)	
	ϵ_1/k, interaction energy of oxidizer ($^{\circ}K$)	
	ϵ_2/k, interaction energy of fuel ($^{\circ}K$)	
	ϵ_j/k, interaction energy for each species ($^{\circ}K$)	

4. ORGANIZATION OF DECK



5. INPUT FORMAT

The input cards may be divided into two types: (1) propellant property cards and (2) problem cards.

The propellant property cards contain all the data shown in Section 3 for the particular propellant system being run. The properties are those of the fuel and oxidizer (both liquid and vapor) and the species comprising the combustion gases.

<u>Input Format for the Propellant Property Cards:</u>

*Read Propellant Combination Title (A Format) in Fields 1-10, and 11-20.

*Read NR, NSP, NTL(1), NTL(2), NTFLM(1), NTFLM(2), NT use I10 format.

*Read NSP species names, (Fields of 12), 6 fields to a card, in same order that species concentrations will be read.

*Read O/F ratios (F format), seven values to a card, until NR O/F ratios are listed.

<u>For each of up to 3 pressures:</u>

*Read pressure.

*For each species, read composition as function of O/F (seven values per card). Start new card for each species.

*Read average molecular weight versus O/F.

*Read gas temperature versus O/F.

GO BACK AND START NEXT PRESSURE

*Read ln gamma versus O/F (at any selected pressure).

*Read NT temperatures.

*Read viscosity ($x10^6$) versus NT for each species. Start new card for each species.

*Read specific heat versus NT for each species. Start new card for each species.

---

*means start new card

*Read in molecular weight for each species. Be sure to maintain correct species order in all input data.

*Read species interaction energy for each species.

*Read propellant molecule interaction energy for ox, then fuel (in second field).

*Read species molecular diameter for each species.

*Read propellant molecular diameter for ox, then fuel.

*Read molecular weight of ox, then fuel.

*Read oxidizer liquid temperature, vapor pressure, liquid density, liquid specific heat, and heat of vaporization (F format). Continue on new card up to NTL(1) valves of oxidizer liquid temperatures.

*Repeat preceding for fuel (NTL(2) cards).

*Read oxidizer vapor film temperature, vapor viscosity ($x10^6$), vapor conductivity ($x10^6$), and vapor specific heat for NTFLM(1) valves of oxidizer film temperature.

*Repeat above for fuel (NTFLM(2) cards).

*Read LØØse: I10 format

Fuel decomposition flame exists, LØØSE = 1

No fuel decomposition flame exists, LØØSE = 0

Definitions

NR = Number of O/F ratios

NSP = Number of species

NTL = Number of liquid phase temperature

NTFLM = Number of gas phase (vapor film) temperatures

NT = Number of species gas phase temperatures

(1) = Oxidizer

(2) = Fuel

Follow above propellant property data with engine data, as shown on coding sheet.

Input Format for Problem Cards

(See chart following).

Card 9 describes the geometry of a conventionally shaped combustion chamber according to the following definitions:

Par 1 = Z_c, inches

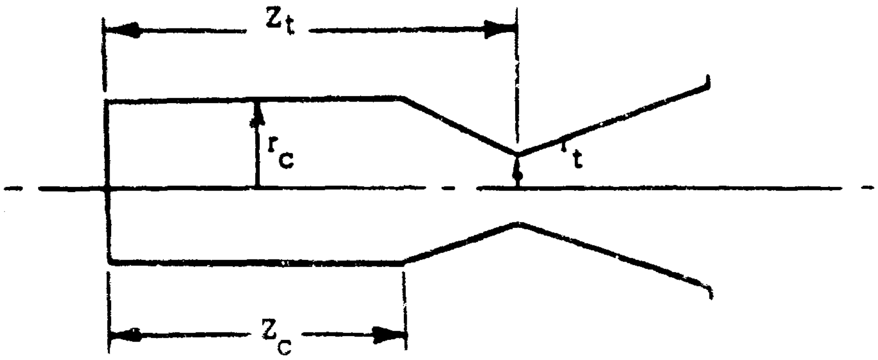
Par 2 = πr_c^2, in^2

Par 3 = (Par 4) $Z_c + r_c$, inches

Par 4 = $(r_c - r_t)/(Z_t - Z_c)$, dimensionless

Par 5 = 2π (Par 4)^2, dimensionless

Par 6 = 2π(Par 3)(Par 4), inches



Input for Sample Problem

See following pages.

INPUT FORMAT FOR PROBLEM CARDS

1–10	11–20	21–30	31–40	41–50	51–60	61–72	73–80
			COMMENT				Card #1 1 0 A 6
			COMMENT				Card #2 1 0 A 6
COMMENT							Card #3 1 0 A 6
XSTART, Inches (Norm. -1.0)	Max. Step Size (Norm. -.03 to .2)	Min. Error (Norm. -.0001)	Max. Error (Norm. -.01)	XSTOP-inches	Init. Gas velocity at X=0, in/sec		Card #4 7 E 1 0 . 6
NSW-Print indicator (Norm. -0)	MP=Power of 2 variation between max. and min. step (Norm. 7-4)	Print every NO cycles (Norm. -1)	NPLOT=1, NO NPLOT=2, YES	Print every KPRINT cycles of Max. step			Card #5 6 I 1 0
Chamber Pressure, Psia	Min. M.R. (Norm. -0.6)	Max. M.R. (Norm. -5.0)	Throat Area (in^2)	Max. Chamber Area (in^2)	Sto'c. M.R.	5 E 1 0 .	Card #6 6 I 1 0
Flow Rate (lb/sec)	Inj. Velocity (in/sec)	Inj. Liquid Temp (°R)	Mass median Drop Radius (in)	Std. Dev. of Drop Size (Norm. -2.3)	No. of Drop Groups	†Oxidizer 5 E 1 0 .	Card #7 6 I 1 0
	This card same as #7 but values given for fuel					†Fuel 5 E 1 0 .	Card #8 6 I 1 0
PAR 1*	PAR 2*	PAR3*	PAR 4*	PAR 5*	PAR 6*		Card #9
	*Chamber Geometry Parameters, see next page for definitions						

FORM 292-B

INPUT FOR SAMPLE PROBLEM

```
      NTO            N2H4
           9              9         10         13          7          6          6
             4              H2           H2O          N2              HO           O2
           H3N              NO             0
15.        10.         5.         2.         1.         .5         .2
.1         .065
100.
                                  .007       .02        .001

                                  .020       .180       .408       .560

.612       .531
.113       .161        .274       .425       .388       .219       .090
.046       .030
.351       .360        .375       .391       .392       .369       .348
.340       .339
                       .005       .045       .013

.533       .479        .339       .079       .002



                       .011       .020

                                  .090

29.01      29.32       26.58      22.74      18.75      15.13      12.53
11.62      11.32
1903.      2533.       3855.      5290.      5278.      4018.      2693.
2150.      1964.
100.
                                  .004       .015

                                  .016       .179       .410       .560

.612       .528
.113       .161        .274       .437       .396       .219       .090
.045       .030
.351       .360        .372       .395       .396       .396       .348
.341       .337
                       .002       .041       .011

.533       .479        .339       .076


           .002
                       .011       .020

                                  .007

29.02      28.32       26.59      22.90      18.88      15.14      12.53
11.63      11.33
1933.      2533.       3652.      5429.      5308.      4025.      2695.
2158.      1969.
1000.
```

			,002	,009		
			,012	,180	,411	,559
,609	,625					
,113	,160	,279	,447	,402	,220	,090
,045	,039					
,391	,360	,373	,394	,309	,370	,347
,340	,337					
			,037	,007		
,536	,477	,339	,076			
,003	,005					
		,010	,023			
			,004			
29,01	28,32	26,5	23,05	18,96	15,14	12,54
11,66	11,38					
1903,	2532,	3872,	5558,	5564,	4014,	2696,
2145,	1984,					
1,310	1,287	1,253	1,225	1,232	1,268	1,318
1,344	1,353					
540,	1080,	1980,	3060,	4860,	7020,	
,419	,659	,975	1,292	1,741	2,207	
,50	,792	1,179	1,564	2,108	2,672	
,614	1,203	2,202	3,252	4,693	6,121	
,995	1,528	2,357	3,146	4,242	5,378	
1,102	1,781	2,640	3,511	4,737	6,004	
1,156	1,912	2,853	3,796	5,130	6,506	
,593	1,173	2,062	2,932	4,109	5,283	
1,075	1,795	2,697	3,571	4,833	6,130	
1,056	1,747	2,616	3,468	4,687	5,944	
2,5	2,5	2,5	2,5	2,5	2,5	
7,0	7,05	7,35	7,99	8,62	9,11	
8,08	8,73	10,22	11,75	13,2	14,01	
7,0	7,24	8,0	8,51	8,85	8,99	
7,0	7,04	7,45	8,09	8,73	9,1	
7,07	7,7	8,47	8,89	9,44	9,92	
8,55	10,72	14,0	16,53	18,43	19,35	
7,17	7,5	8,28	8,60	8,97	9,12	
5,26	5,09	5,02	5,01	5,02	5,12	
1,	2,	18,	28,	17,	32,	17,
30,	16,					
37,	59,7	809,	71,4	79,8	106,7	558,
116,7	106,7					
331,9	502,8					
2,71	2,83	2,54	3,80	[illegible],15	3,47	2,9
3,49	3,05					
3,969	4,029					
46,	32,					
400,	,27	,033	,35	435,		
440,	,85	,0536	,35	43[illegible],		
480,	3,94	,0541	,353	422,		
520,	11,8	,0527	,372	412,		

```
560.      30.       .03085    .388      403.
600.      80.       .0487     .414      392.
640.      180.      .0463     .464      379.
680.      330.      .0435     .543      365.
720.      660.      .03935    .70       344.
760.      1200.     .0324     .87       315.
400.      .001      .035      .686      700.
500.      .08       .0356     .70       680.
550.      .48       .0357     .72       650.
600.      1.9       .0348     .74       620.
650.      6.0       .0338     .75       590.
700.      15.5      .0328     .77       550.
750.      37.       .0317     .78       510.
800.      75.       .0305     .80       470.
850.      160.      .0292     .82       430.
900.      250.      .0281     .83       390.
950.      430.      .0270     .85       370.
1000.     660.      .0260     .87       340.
1050.     960.      .0250     .89       310.
400.      .524      .094      .231
600.      .92       .224      .238
1000.     1.57      .485      .253
1600.     2.34      .675      .269
2400.     3.21      1.39      .286
3200.     3.91      1.91      .297
4000.     4.57      2.44      .300
400.      .42       .14       .32
800.      .80       .30       .50
1200.     1.18      .45       .61
2000.     1.95      .95       .74
2800.     2.71      1.5       .82
4000.     2.85      2.4       .90
          1
N2H4-MMH STABILITY 7 JAN69 RUN  183 (DOUBLET-N2H4) INGFBO
DELV= VINJ   NO  CORRECTIONS
ICRPG 5TH  CONF.
0.0       .05       .0001     .01       1.5       0.0
          0         4         1         1         1
311.      .2        8.        12.46     128.8     1.4
12.99     648.      534.      .00555    2.3                 5
11.24     1609.     532.      .00280    2.3                 5
5.        128.8
```

6. PROGRAM LISTING

```
              PROGRAM STEADY(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
        $IBFTC TRSL    LIST,REF
000003        COMMON /E/FC,NM/R/BD/C/TA/FP/AR,AU,BCDX,BCDY,LOR
000003        COMMON /LINKA/ LOOSE
000003        COMMON /PRPS/ PRPSYS(4) /SPEC/ NSP, SPNAME(2, 15)
000003        DIMENSION FC(80),NM(20),BD(10,20,12),TA(1000),AR(150),
             1 AU(100,90),BCDX(7),BCDY(3),LOR(9),TITLE(24)
             2,EM(10,20,2), DM(10,20,2),TLA(10,20,2), DT(10,20,2)
             3,V(10,20,2), DV(10,20,2), WTMOL(2)
000003        EQUIVALENCE (FC(14), TSTOP), (NM(5), NPTN), (BD(1, 1, 1), EM(1, 1,
             11)), (BD(1, 1, 3), DM(1, 1, 1)), (BD(1, 1, 5),TLA(1, 1, 1)), (BD(1
             2, 1, 7), DT(1, 1, 1)), (BD(1, 1, 9), V(1, 1, 1)), (BD(1, 1, 11), D
             3V(1, 1, 1)), (FC(1), T), (NM(15), NPLOT), (TA(46), WTMOL)
000003        COMMON                   /TRFGAM/ FGAMT(13) /OF/ R(15), NR /CMPTAR/
             1YSP(15, 15, 3) /PRSSR/ PRSS(3) /PVY/ PV(15, 2) /TLX/ TL(15, 2) /DT
             2L/ NTL(2) /TFLMX/ TFILM(15, 2) /VISCVY/ VVIS(15, 2) /DTFLM/ NTFLM(
             32) /RHOY/ RHOL(15, 2) /KVAPY/ KVAP(15, 2) /CPVPY/ CPVAP(15, 2) /CP
             4Y/ CP(15, 2) /LAMY/ LAM(15, 2) /WTM/ WMTAB(15, 3) /TGI/ TC1(15, 3)
             5/TABT/ TTAB(15) /VKSGS/ VSP(15, 15), CPTAB(15, 15) /BT/ NT /DIFFUS
             6/ EPSI(15,2), SIGMA(15, 2), EPSOF(2), SIGOF(2) /MW/ WM(15)
000003        REAL KVAP, LAM
000003        READ (5, 601) PRPSYS
000011    601 FORMAT (4A5)
000011        READ (5, 60) NR, NSP, NTL, NTFLM, NT
000027     60 FORMAT (7I10)
000027        READ (5, 603)(SPNAME(1, I), SPNAME(2, I), I = 1, NSP)
000046    603 FORMAT (12A6)
000046        READ(5,901)( R(I) , I=1,NR )
000061        DO  15  IND=1,3
0000[illegible]        READ(5,901) PRSS(IND)
0000[illegible]        DO 12 I=1,NSP
000072        READ(5,901)    (  YSP( J,I,IND), J=1,NR  )
00010[illegible]   12   CONTINUE
00011[illegible]        READ(5,901) ( WMTAB(I,IND), I=1,NR )
000125        READ(5,901) ( TC1( I,IND) ,I= 1,NR)
000141   15   CONTINUE
000143        READ(5,901) ( FGAMT(J),J=1,NP)
000156        READ(5,901)( TTAB(I), I=1,NT)
000171        DO 17 I=1,NSP
000173        READ (5,901) ( VSP(J,I),J=1,NT)
000206   17   CONTINUE
000211        DO 19 I=1,NSP
000217        READ (5,901) ( CPTAB(J,I), J=1,NT)
000225   19   CONTINUE
000230        READ(5,901) ( WM(I), I=1,NSP)
000242        READ(5,901) ( EPSI(I,1),I=1,NSP)
000255        READ(5,901) EPSOF
000263        READ(5,901) ( SIGMA(I,1), I=1,NSP)
000274        READ(5,901) SIGOF
000304        READ(5,901) WTMOL
```

```
000312          DO 20  I=1,2
000314          NTLCT=NTL(I)
000316          READ(5,902) ( TL(J,I) , PV(J,I),RHOL(J,I),CP(J,I), LAM(J,I),
              1     J=1,NTLCT )
000346     20   CONTINUE
000350          DO 23  I=1,2
000352          NTFCT= NTFLM(I)

000354          READ(5,903) (TFILM(J,I),VVIS(J,I),KVAP(J,I),CPVAP(J,I),J=1,NTFCT)
000401     23   CONTINUE
000403          READ(5,904) LOOSE
000411    901   FORMAT( 7E10,4)
000411    902   FORMAT( 5E10,4)
000411    903   FORMAT( 4E10,4)
000411    904   FORMAT(I10)
000411        5 CALL REED
000412            CALL DRG
000413            CALL RSET
000414      10     CALL PROP(NSP)
000416            CALL DERIV(NSP)
000420             CALL VADM(DM,EM,1)
000423             CALL VADM(DT,TLA,2)
000426             CALL VADM(DV,V , 3)
000431             CALL SUM
000432              IF(NPTN) 40,35,40
000433      35    CALL PRINT
          C         CONTROLS STEP PRINT AND STORES PLOT VALUES
          C        NEXT TEST FOR TIME STOP
000434              IF( T - TSTOP) 40, 38, 38
000437     38   IF(NPLOT .NE. 0) GO TO 5
000440          CALL PLOTT
000441             GO TO 5
000442      40    CALL SHIFT
000443             GO TO 10
000444   12345 CALL EXIT
000445             END
```

```
              FUNCTION A(X)
000003        COMMON / ADDPRM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000003        IF (X .GT. PAR1) GO TO 1
000006        A = PAR2
000007        RETURN
000007      1 A = 3.1416 * (PAR3 - PAR4 * X) ** 2
000013        RETURN
000014        END
```

```
              FUNCTION AP(X)
000003        COMMON / ADDPRM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000003        IF (X .GT. PAR1) GO TO 1
000006        AP=0.
000006        RETURN
000007      1 AP = PAR5 * X - PAR6
000012        RETURN
000013        END
```

```
              SUBROUTINE BOIL(J,I)
000005        DIMENSION FB(80),NM(20),BD(10,20,12),TA(1000),BETA(20,2),RS(20,2)
             1,FNUM(20,2),WW(20,2),DM(10,20,2),DT(10,20,2),V(10,20,2),
             2  TL(10,20,2)  ,EM(10,20,2), FNUH(20,2)
000005        EQUIVALENCE (TA(30),P),(TA(392),RV),(TA(474),FKAV),
             1 (TA(25),TWOPI), (TA(475),CPA),(TA(482),GJR),(TA(264),TG),
             2 (TA(647),BETA),(TA( 96),RS), (TA(433),FNUM), (BD(401),DM),
             3 (BD(1201),DT), (BD(801), TL), (BD(1),EM), (BD(1601),V)
             4, (TA(482), GJR) ,(TA(393),FNUH) ,(TA(216),WW)
000005        COMMON/E/FC,NM/B/BD/C/TA
000005  150   TB = TBL(P,I)
000011        WRITE(6,2000) J,I
000021  2000  FORMAT (1X, 5HDDROP, I2, I3, 10HIS BOILING)
000021        K1 = 0
000022        W1 = AMIN1(ABS(-DM(2, J, I) * V(1, J, I)), 1.E-6)
000043        RRS = RV*RS(J,I)**2
000050        COE = FNUH(J,I)*FKAV*RS(J,I)*TWOPI/CPA
000062        COE  = ABS(COE)
000063  152   W = COE * ALOG(1. + CPA * (TG - TB) / (ALM(TB, I) + GJR * (W1 / RR
             1S) ** 2))
000105        WR = ABS((W - W1) / W)
000110        K1 = K1 + 1
000112        IF (K1 .GT. 15) GO TO 154
000115  153   W1 = (W+W1)/2.0
000120        IF (WR .GT. .02) GO TO 152
000123  154   DM(1,J,I) = -W/V(1,J,I)
000137        DT(1,J,I) = 0.0
000143        TL(1,J,I) = TB
000151        BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000164        WW(J,I) = W
000170        RETURN
000170        END
```

```
                [illegible]
                DRAG COEF OF DROP
[illegible]     IF (RE-30.)10,10,20
000005       10 CD = AMIN1(50., 27.*RE**(-.84))
000014          RETURN
000015       20 IF(RE-1.E4)30,30,40
000020       30 CD =0.271*RE**.217
000025          RETURN
000025       40 CD=2.
000027          RETURN
000027          END
```

```
                  SUBROUTINE DERIV(NSP)
000003          COMMON /E/FC,NM/B/BD/C/TA
000003          COMMON /LINKA/ LOOSE
000003          DIMENSION  FC(80),NM(20), BD(10, 20, 12), TA(1000),NSET(2)
               1, ENMP(2), KDISC(20,2), VD(20,2), EM(10,20,2),TL(10,20,2)
               2,V(10,20,2), RS(20,2), WTMOL(2), PR(20 ,2), SC(20,2), RE(20,2)
               3,REP(20,2), FNUH(20,2), FNUM(20,2),DM(10,20,2), DT(10,20,2)
               4,DV(10,20,2) ,EMINT(20,2)
000003          EQUIVALENCE  (TA(46),NSET), (TA(479),ENMP), (TA(270),KDISC)
               1,(TA(257),RAT),(TA(30),P),(TA(476), PA), (TA(475), CPA)
               2,(TA(392), RV) ,  (TA(311), VD), (TA(28),FTPI),(TA(29), THRD)
               3,(BD(1), EM) ,(BD(801), TL), (BD(1601), V) ,(TA(96), RS)
               4,(TA(25), R), (TA(48), WTMOL),(TA(478),U) , (TA(391), RHOVS)
               5,(TA(483),WTML), (TA(474), FKAV), (TA(473), DPOT),(TA(487), PR)
               6,(TA(527),SC),  (TA(567), RE),  (TA(607),REP), (TA(393),FNUH)
               7,(TA(433),FNUM),(BD(401),DM), (BD(1201),DT) ,(BD(2001), DV)
               8,(TA(484), RHOG),(TA(264),TG) ,(TA(56),EMINT)
          C
000003          P2 = P*2.
000005      120 DO 200 I=1,2
000007          N=NSET(I)
000011          ENMP(I)=0.
000013          DO 200  J=1,N
000014           KDISC(J,I) = 0
000020           IF(EM(1,J, I)) 200, 200, 130
000025      130  TBR =(TG + TL(1,J,I))/2.
000035             CALL VKSGAS (RAT,P,TBR,VISB,FKB,CPB,NSP)
000043          PA=AMIN1(.99*P,PVAP(TL(1,J,I),I))
000057          PA2P=PA/P2
000061          DPA2P=1.-PA2P
000063          CPA=CVAP(TBR,I)
000066               RH = RHO(TL(1,J,I) ,I)
000076               RV = WTMOL(I)*P/R/TL(1,J, I)
000107               VD(J,I) = U - V(1,J,I)
000120               RS(J,I) = (EM(1,J,I)/FTPI/RH)**THRD
000134             RE(J, I) = RS(J, I) * RHOVS * ABS(VD(J, I))
000147             WTMAV = PA2P*WTMOL(I) + DPA2P*WTML
000153             VISAV = VISCV(TBR,I)*PA2P + DPA2P*VISB
000161             FKAV = PA2P*FKA(TBR,I) + DPA2P*FKB
000167             RHOAV = P*WTMAV/R/TBR
000173             CPAV = (PA2P*WTMOL(I)*CPA + DPA2P*WTML*CPB)/WTMAV
```

```
000202            REP(J, I) = 2. * RS(J,I) * RHOAV * ABS(VD(J, I)) / VISAV
000215                 PAIP = PA / 2.
000217              CALL DIFFU (RAT,P,TBR,PAIP,1,DFU,NSP)
000226              DPOT = DFU*P/TBR
000231               PR(J,I) = CPAV*VISAV/FKAV
000237               SC(J,I) =VISAV/RHOAV/DFU
000244            IF (PR(J, I) .GT. 0. .AND. SC(J, I) .GT. 0.) GO TO 979
000261      978    WRITE (6,797) PR(J,I),SC(J,I)
000277      797    FORMAT(1H0,18HSTATEMENT 978 PR =, F10.3,6H  SC =,F10.3)
000277      979 RTRE = SQRT(REP(J, I))
000305               FNUM(J,I) =  2.0 + .6*SC(J,I)**THRD*RTRE
000321               FNUH(J,I) =  2.0 + .6*PR(J,I)**THRD*RTRE
          C        CHECK FOR ENTRANCE TO DISSOCIATION LOOP
000333           IF (LOOSE .EQ. 0) GO TO 149
000335           GO TO (149, 160), I
000343      160 CONTINUE
000343              BEE =  2.* RS(J,I)/(FNUH(J,I) - 2.)
000354           CALL DVCHK(KNOW)
000356           GO TO (161, 162), KNOW
000365      161 BEE = 1.E30
000367      162      RL = RT( RS(J,I))
000375             IF(BEE- RL) 149,163, 163
000400      163      CALL TWFL (J,I)
000402               GO TO 156
000404      149 PMDP=0.99*P
000406          IF (PA .LT. PMDP) GO TO 155
000411      150      CALL BOIL (J,I)
000413             GO TO 156
000415      155   CALL VAPOR(J,I)
000417      156 DV(1, J, I) = RHOG * .375 / RS(J, I) * ABS(VD(J, I)) / V(1, J, I
              1* VD(J, I) / RH * CD(RE(J, I))
000451      200                 CONTINUE
000457               RETURN
000457               END
```

```
                  FUNCTION  FGAM(OFR)
000003          COMMON /OF/ R(15), NR /TRFGAM/ FGAMT(15)
000003          CALL LNGRIN (OFR, FGAM, R, FGAMT, DFDT, NR)
000007            RETURN
000011            END
```

```
                    SUBROUTINE  LNGRIN (ARG,YARG,X,Y,DYDX,N)
000011              DIMENSION X(1),Y(1)
              C
000011              NN=N
              C
000011              IF(NN.NE.1) GO TO 1
000014               YARG=Y(1)
000014               DYDX=0.
000015               RETURN
              C
000016         1    XV=ARG
000017               IF(X(NN) .LT. X(1)) GO TO 3
000023              DO 2 J=2,NN
000024               IF(X(J).GE.XV) GO TO 6
000027         2    CONTINUE
000032               GO TO 5
000032         3    DO 4 J=2,NN
000034               IF(X(J).LE.XV) GO TO 6
000037         4    CONTINUE
000042         5    J=NN
000044         6    I=J-1
000046              DYDX=(Y(J)-Y(I))/(X(J)-X(I))
000054              YARG=Y(I)+DYDX*(XV-X(I))
              C
000061              RETURN
000061              END
```

```
              SUBROUTINE LOGNRM(RM,SIG,N,RS)
       C      COMPUTES RADII OF N DROPS ABOUT WHICH 1/N TH OF THE MASS IS
       C      CENTERED IN THE LOGARITHMICO-NORMAL DISTRIBUTION WITH MASS-MEAN
       C      RADIUS RM AND STANDARD DEVIATION LN SIG.  XP, THE INVERSE
       C      PROBABILITY FUNCTION IS APPROXIMATED BY A RATIONAL FRACTION.
000007        DIMENSION RS(20)
000007        DEL = 1. / FLOAT(N)
000010        SIGLN = ALOG(SIG)
000015        P=-DEL/2.
000017        NP4 = N+4
000021        MED = (N+1)/2 + 4
000023        J = NP4
000025        DO 4 I = 1,NP4
000027        IF(I-2)10,15,11
000031     10 P=P+ 0.6*DEL
000034        GO TO 2
000035     11 IF(I-5) 15,15,20
000040     15 P=P+0.2*DEL
000043        GO TO 2
000044     20 P=P+DEL
000046     30 IF (I .GT. MED) GO TO 5
000052      2 T = SQRT(-ALOG(P * P))
000060        XP=T-(2.30753+.27061*T)/(1.+T*(.99229+.04481*T))
000072        ESIGX = EXP(SIGLN * XP)
000075        IF(I-3)4,3,40
000103     40 IF(I-5)4,49,50
000106     49 P = DEL/2.0
000110        GO TO 4
000111     50 J=N - I + 9
000114      3 RS(J)=RM*ESIGX
000117      4 RS(I)=RM/ESIGX
000124      5 RETURN
000125          END
```

```
              SUBROUTINE MASSET(EMO,RHO,RS,EMDOT,N,DROPN)
000011        DIMENSION EMO(20),RS(20),DROPN(20)
000011        CRHO=4.188790204*RHO
000012        FRAC = EMDOT / FLOAT(N)
       C
000014        FRAC1 = FRAC/5.0
000016        NP4 = N+4
000020        DO 2 I =1,5
000021        EMO(I) = CRHO*RS(I)**3
000024      2 DROPN(I) = FRAC1/EMO(I)
000031        DO 5 I=5,NP4
000033        EMO(I)=CRHO*RS(I)**3
000036      5 DROPN(I)=FRAC/EMO(I)
000043        RETURN
000044          END
```

```
              SUBROUTINE NADM(YP,Y,KK)
000006         DIMENSION YP(210), Y(210), FC(80), NM(20),  WT(3),NST(2),NED(2)
000006        COMMON /E/  FC,NM
000006        EQUIVALENCE (FC(3),H), (FC(11),WT), (FC(10), E1), (FC(9), EMAX),
             1 (FC(8), EMIN), (NM(2), INDR), (NM(7), NSW), (NM(4), MGAM),
             2 (NM(3), MALP),(NM(17),NST),(NM(19),NED)
        C     ******************************************************************
        C     MGAM=-1,0,1 INDICATES PREDICTOR-RUNGE-KUTTA OR CORRECTORPHASE
        C     MALP-INDICATES PERT OF RUNGE KUTTA PHASE
        C     NSW- PRINT SWITCH FOR ERROR INDICATION
        C     E1 - CINTAINS MAXIMUM ERROR FOR EACH CYCLE
        C     YP - ADDRESS OF DERIVATIVE ARRAY
        C     Y - ADDRESS  OF THE ORDINATE ARRAY
        C     ******************************************************************
000006        IF (MGAM) 40, 10,  60
        C     ******************************************************************
        C     THIS ROUTINE EMPLOYS A FOURTH ORDER RUNGE-KUTTA STARTER
        C     ******************************************************************
000010     10 IF(MALP - 2) 20, 15 ,15
000013     15    K = 4 - MALP
000015           DO 18 KL = 1,2
000017           LS = NST(KL)
000021           LE = NED(KL)
000023           DO 18 I = LS,LE,10
000025           J = I + K
000027           Y(I+9) = Y(J) + H*YP(I)
000034     18 CONTINUE
000040        GO TO 99
000041     20   DO 22 KL = 1,2
000043           LS = NST(KL)
000045           LE = NED(KL)
000047           DO 22 I = LS,LE,10
000051           Y(I+9) = Y(I+3) + H/6,*(YP(I)+2,*(YP(I+1)+YP(I+2)) + YP(I+3))
000064     22 CONTINUE
000070        GO TO 99
        C     ******************************************************************
        C     ADAMS-BASHFORTH FIFTH ORDER PREDICTOR FORMULA
        C     ******************************************************************
000070     40  DO 42 KL = 1,2
000072           LS = NST(KL)
000074           LE = NED(KL)
000076           DO 42 I = LS,LE,10
000100           Y(I+9) = Y(I) + H*(2,6402777777*YP(I) -3,8527777777*YP(I+1)
             1 + 3,6333333333*YP(I+2) - 1,7694444444*YP(I+3)
             2 + ,3486111111*YP(I+4))
000120     42 CONTINUE
000124        GO TO 99
        C     ******************************************************************
        C     ADAMS MOULTON FIFTH ORDER CORRECTOR FORMULA
        C     ******************************************************************
```

```
000125        60    DO 98 KL = 1,2
000127              LS = NST(KL)
000131              LE = NEN(KL)
000133              DO 98 I = LS,LE,10
000135              Y(I) = Y(I+1)+H*(.34861111111*YP(I)+ .89722222222*YP(I+1)-
                  1 0.3666666666*YP(I+2) + .14722222222*YP(I+3)
                  2 - .02638888888*YP(I+4))
000154        62 ER= ABS(Y(I) - Y(I+9))*WT(KK)
000162              IF(Y(I))  70, 80, 70
000164        70  ER = ER/ ABS(Y(I))
000170        80  IF(ER - EMAX) 85, 95, 95
000173        85  IF(ER- EMIN) 98, 87, 87
          C        ******************************************************************
          C        RELATIVE ERROR CHECK-BRANCH TO 99 INDICATES ERROR SMALLER THAN
          C        ALLOWABLE ERROR-ADDING ONE TO INDR INDICATES VARIABLE WITHIN
          C        ERROR ALLOWED
          C        ******************************************************************
000176        87 INDR = INDR  + 1
000200           IF(NSW) 88, 98, 88
000201        88  WRITE ( 6,2)  KK
000207         2  FORMAT(1H0, 8HVARIABLE, I3, 13HWITHIN LIMITS)
000207              GO TO 98
          C        ******************************************************************
          C        ONE HUNDRED IS SUBTRACTED FOR EACH VARIABLE LARGER THAN THE
          C        ERROR LIMITS
          C        ******************************************************************
000212        95  INDR =  INDR - 100
000214           IF(NSW) 97, 98, 97
000215        97  WRITE( 6,3)  KK
000223         3 FORMAT(1H0, 8HVARIABLE, I4, 20HOUTSIDE ERROR LIMITS)
          C        ******************************************************************
          C        E1 CONTAINS MAXIMUM ERROR OCCURING DURING THE CYCLE
          C        ******************************************************************
000223        98  E1 = AMAX1(ER,E1)
000235        99  RETURN
000236            END
```

```
                  SUBROUTINE ORG
000002            DIMENSION FC(80), NM(20), W(3),NSET(2),NST(2),NED(2),TA(100)
000002             COMMON /E/ FC, NM /C/TA
000002             EQUIVALENCE (FC(1),T), (FC(2),RKT), (FC(3),H), (FC(4),HO),
                 1 (FC(5), HMIN), (FC(6),HMAX), (FC(7),HZD2), (FC(8),EMIN),
                 2(FC(9),EMAX), (FC(11),W), (FC(10),E1),
                 3 (NM(1),IM), (NM(2),INDR), (NM(3),HALP), (NM(4),MGAM),
                 4 (NM(5),MPTN), (NM(6),MPTS), (NM(7),NSW), (NM(8),NCOU),
                 5 (NM(9),MP), (NM(10),NV) , (NM(11), NO)
                 6,(TA(46),NSET), (NM(17),NST),      (NM(19), NED)
            C     ****************************************************************
            C           DESCRIPTION OF THE LISTED VARIABLES
            C     T - THIS CELL CONTAINS CURRENT INTEGRATION TIME
            C     RKT - START TIME OR PREVIUUS BEGINING OF RK TIM5
            C     H - CURRENTLY USED STEP SIZE IN COMPUTING
            C     HO - STORED STEP SIZE
            C     HZD2 - HALF OF STORED STEP SIZE
            C     HMIN - MINIMUM STEP SIZE
            C     HMAX - MAXIMUM ALLOWABLE STEP
            C     EMIN - EMAX MIN AND MAX AOLOWABLE ERROR
            C     W - ARRAY OF WEIGHTS TO WEIGHT ERROR CINSIDERATION
            C     IM - NO OF GOOD POINTS FROM R,K START
            C     INDR - INDICATOR FOR ERROR OUTSIDE OR WITHIN MIN MAX TOLERANCE
            C     HALP - COUNTER FOR R,K INTRRMEDIATE POINTS
            C     MGAM - PHASE INDICATOR -1,PREDICTOR0,R,K  1, CORRECTOR
            C     MPTN - PRINT COUNTER, CURRENT
            C     MPTS - TOTAL NO OF POINTS IN PRINT INTERVAL
            C     NSW - PRINT INDICATOR IN NADM ROUTINE
            C     NCOU - TOTAL NO OF COMPUTED POINTS DURING INTEGRATION CYCLE
            C     MP - POWER OF 2 VARIATION FROM HMIN TO HMAX
            C     HMAX, MP, NO, NSW, NV AND W(I) MUST EITHER BE READ INTO CORE OR
            C     INITIAIZED BY AN ADDITIONAL ROUTINE
            C     ****************************************************************
000002            HMIN = HMAX/2.**MP
000007            HO = HMIN
000010            HZD2 = HO/2,0
000012            H = HZD2
000013            RKT = T
000014             E1 = 0,0
            C     ****************************************************************
            C      FIXED POINT INITIALIZATIONS
            C     ****************************************************************
000015             IM = 0
000016            MALP = 4
00  ...             MGAM = 0
000020              MPTN = 0
000021            MPTS  = NO*2**MP
000026            INDR = 0
000027            NCOU = 0
000030              NST(1) = 1
000031              NST(2) = 201
000032              NED(1) = (NSET(1)+3)*10+1
000036              NED(2) = (NSET(2) + 3)*10 + 201
            C     ****************************************************************
            C      MPTN SET TO ZERO TO PRINT INITIAL CONDITIONS
            C     ****************************************************************
000042            RETURN

000042            END
```

```
                 SUBROUTINE ORT...
       C
000002            COMMON /E/FC,NM/B/BI/C/TA/FP/AB,A
000002            COMMON /PRNT/ KPRINT
000002            LOGICAL ...
000002            DIMENSION AB(150),AU(100,90),TA(1000), FC(80),NM(20),RD(10,20,12)
                 1 ,ENMP(2),FA(2),EMDOT(2),DN(20,2),RS(20,2),V(10,20,2),BETA(20,2)
                 2 ,VD(20,2),VDOUT(20,2),NSET(2),EM(10,20,2),DM(10,20,2)
                 3 ,EMINT(20,2)
                 4 ,TITLE(24)
                 5 ,TL(10,20,2),           KDISC(20,2)
                 6 ,DNT(2),RE(20,2)
                 7 ,S(12,2),XM(3),XTAB(20),YTAB(20),TM(2),RB(6,3),XL(3)
                 8 ,DVB(6,3),RED(6,3),DRAG(3)
000002            EQUIVALENCE (FC(1),X),(TA(33),AXMIN),(TA(257),RAT),(TA(35),
                 1OFSTOC), (TA(479),ENMP),(TA(258),EMD),(TA(50),FA), (TA(486),SDSPD)
                 2,(TA(36),EMDOT),(TA(96),RS)             ,(TA(136),DN),(RD(1401),V),
                 3 (TA(647),BETA), (TA(311),VD), (TA(478),U), (TA(264),TG),(TA(265),
                 4 TSTG),(TA(38),P), (TA(266),PD),(TA(405),EMACH), (TA(46),NSET),
                 5 (RD(1),EM), (TA(56),EMINT),(RD(401),DM) ,(TA(1),TITLE)
                 6,(RD(801),TL), (TA(270), KDISC), (TA(52),DNT)
                 7,(TA(391),RHOVS), (TA(481),PHI),(NM(13),IPLOT),(TA(29),THRP)
                 8,(FC(3),DX), (NM(12),JZ), (NM(14), IRZ) ,(TA(567),RE)
                 9 ,(TA(484),RHOG),(TA(486),SDSPD)
       C
000002            AX = A(X)
000005            PHIP = -(ENMP(1) + ENMP(2))
000007            RAN = SQRT (AX/3.14159)
000014            ETA = AX / AXMIN
000016            IF(RAT -OFSTOC)  31,31,32
000020         31 RCOMB = -ENMP(1) * (1./OFSTOC + 1.) / EMD
000025            FCOMB = FA(1) * (1. + 1./OFSTOC) / EMD
000030            GO TO 33
000030         32 RCOMB = -ENMP(2) * (OFSTOC + 1.) / EMD
000034            FCOMB = FA(2) * (1.+OFSTOC) / EMD
000036         33 RLCOMB = RCOMB * RAN / ETA
000041            REC=RHOVS*SDSPD
000043            FVAP1=FA(1)/EMDOT(1)
000045            FVAP2=FA(2)/EMDOT(2)
000047            FVAP = (FA(1) + FA(2))/EMD
000051            RVAP1=-ENMP(1)/EMDOT(1)
000053            RVAP2=-ENMP(2)/EMDOT(2)
000055            RVAP= PHIP/EMD
       C
000056            ITEST   ...  IPLOT + IPLOT - IRZ
000063            IF (ITEST) 328, 324, 328
000064        324 CONTINUE
000064            GO TO 1
000065        328 AB(JZ) = X
000070            AU(JZ,1) = RAT
000072            AU(JZ,2) = FVAP2
000073            AU(JZ,3) = FVAP1
000075            AU(JZ,4) = FVAP
000076            AU(JZ,5) = RVAP2
000100            AU(JZ,6) = RVAP1
000101            AU(JZ,7) = RVAP
000103            AU(JZ,8) = EMACH
```

```
000104           AU(JZ,49) = U
000106           AU(JZ,50) = FCOMB
000107           AU(JZ,51) = RCOMB
000111           AU(JZ,19) = R
000112           AU(JZ,29) = RO
000114           AU(JZ,39) = TG
000115           AU(JZ,49) = TSTG
000117           JZ = JZ + 1
000120         1 CONTINUE
000120       329 IBZ = IBZ + 1
           C
000122           ILLIT = MOD(IBZ - 1, KPRINT) .NE. 1 .AND. KPRINT .NE. 1
000133           IF (ILLIT) GO TO 60
000134           WRITE (6, 330) (TITLE(I), I = 1, 24)
000146       330 FORMAT (1H1/ (1H , 10A6))
000146           WRITE(6,340)K,U,TG,TSTG,P,PO,RAT,EMACH
000172       340 FORMAT(3H0X=F6,3,4H  U=F7,1,4H  T=F5,0,4H TO=F5,0,4H  P=F7,2,
                1          4H PO=F7,2,6H  O/F=F7,3,7H  MACH=F5,3)
000172           WRITE(6,350)FVAP1,FVAP2,FVAP            ,FCOMB
000206       350 FORMAT(26H VAPORIZED FRACTION      OF9,6,4H   FF9,6,7H   BOTHF9,6
                1 ,3X,4HCOMB,F9,6)
000206           WRITE(6,360)RVAP1,RVAP2,RVAP ,RCOMB
000222       360 FORMAT(26H VAPORIZATION RATE/IN    OF9,6,4H   FF9,6,7H   BOTHF9,6
                1 ,3X,4HCOMB,F9,6)
           C
000222           WRITE(6,370)
000226       370 FORMAT(70H0OXIDIZER DROPS   R(MIL)  MASS(LB)  V(IN/SEC) U-V/A  TEM
                1P    NUMBER         )
000226        60 I = 1
000227           N=NSET(I)
000232           DO 380 J=1,N
000233             VDOUT(J,I) = VD(J,I)/SDSPD
000242       375  RPD = DM(1,J,I)/ EMINT(J,I)
000253       377   FRACT = (EMINT(J,I) - EM(1,J,I))/EMINT(J,I)
000265           GO TO 2
000265       379  MNM = J + 8
000267            AU(JZ-1,MNM) = RS(J,I)*1,E+3
000277            MZM = J + 28
000300            AU(JZ-1 ,MZM) = ABS (VDOUT(J,I))
000310            MZN = J + 49
000312            AU(JZ-1,MZN) = V(1,J,I)
000322         2 CONTINUE
000322           IF (ILLIT) GO TO 380
000324            WRITE(6,390)J,RS(J,I),EM(1,J,I),V(1,J,I),VDOUT(J,I),TL(1,J,I),
                1 DN(J,I), FRACT, RPD
000373       390 FORMAT(13X,I2,3PF9,4,0PE13.5 ,      F5,0,F9,4,F8,2,E11,3,4X,
                1  E11,3,4X,E11,3)
000373       380 CONTINUE
           C
000376           IF (ILLIT) GO TO 61
000377           WRITE(6,400)
000403       400 FORMAT(12H0FUEL DROPS    )
000403        61 I = 2
000404           N=NSET(I)
000407           DO 410 J=1,N
000410             VDOUT(J,I) = VD(J,I)/SDSPD
000417       405 RPD = DM(1,J,I)/EMINT(J,I)
000430       407  FRACT = (EMINT(J,I) - EM(1,J,I))/EMINT(J,I)
```

```
000433          [illegible]
000447     137  MXM = J + 18
000444          AJ(JZ-1,MXM) = RS(J,I)*1.E+3
000454           MZM = J + 38
000455          AJ(JZ-1 ,MZM) = ABS (VDOUT(J,I))
000465           MZN = J + 59
000467          AJ(JZ-1,MZN) = V(1,J,I)
000477        3 CONTINUE
000477          IF (ILLIT) GO TO 410
000501          WRITE (6,391) J,RS(J,I),EM(1,J,I),V(1,J,I),VDOUT(J,I),
               1 TL(1,J,I),DN(J,I),FRACT, RPD, KDISC(J,I)
000554      391 FORMAT(13X,I2,3PF9.4,0PE13.5 ,        F5.0,F9.4,F8.2,E11.3,
               1  E11.3,4X,E11.3,I15)
000554      410 CONTINUE
          C
000557          DO 10 I=1,2
000560          DO 10 K=1,12
000561     10   S(K,I)=0.
000571          DO 12 I=1,2
000572          N=NSET(I)
000574          DO 12 J=1,N
000576          IF(V(1,J,I).LE.0.) GO TO 12
000603          S(1,I)=S(1,I)+DN(J,I)/V(1,J,I)
000616          S(2,I)=S(2,I)+DN(J,I)/V(1,J,I)*EM(1,J,I)
000635          S(3,I)=S(3,I)+DN(J,I)/V(1,J,I)*RS(J,I)
000652          S(4,I)=S(4,I)+DN(J,I)/V(1,J,I)*RS(J,I)**2
000666          S(5,I)=S(5,I)+DN(J,I)/V(1,J,I)*RS(J,I)**3
000703          S(6,I)=S(6,I)+DN(J,I)*DM(1,J,I)
000714          S(7,I)=S(7,I)+DN(J,I)*DM(1,J,I)*RS(J,I)**2
000730          S(8,I)=S(8,I)+DN(J,I)/V(1,J,I)*BETA(J,I)*RS(J,I)
000746          S(9,I)=S(9,I)+DN(J,I)/V(1,J,I)*BETA(J,I)*RS(J,I)**1.5
000767          S(10,I)=S(10,I)+CD(RE(J,I))*DN(J,I)*EM(1,J,I)
               1                 /RHO(TL(1,J,I),I)/V(1,J,I)/RS(J,I)
001017     12   CONTINUE
001024          XM(1)=S(2,1)/S(1,1)
001026          XM(2)=S(2,2)/S(1,2)
001030          XM(3)=(S(2,1)+S(2,2))/(S(1,1)+S(1,2))
001032          DO 14 I=1,2
001034          N=NSET(I)
001036          DO 13 J=1,N
001040          YTAB(J)=TL(1,J,I)
001046     13   XTAB(J)=EM(1,J,I)
001056          CALL LAGRIN(XM(I),TM(I),XTAB,YTAB,DYDX,N)
001063     14   RB(1,I)=(.238733   *XM(I)/RHO(TM(I),I))**.3333333333
001101          RHO3=(RHO(TM(1),1)*(1.-FVAP1)*EMDOT(1)+RHO(TM(2),2)*(1.-F  P2)*
               1     EMDOT(2))/((1.-FVAP1)*EMDOT(1)+(1.-FVAP2)*EMDOT(2))
001124          RB(1,3)=(.238733   *XM(3)/RHO3)**.3333333333
001131          DO 15 I=1,2
001133          RB(2,I)=(S(5,I)/S(1,I))**.3333333333
001146          RB(3,I)=SQRT(S(5,I)/S(3,I))
001160          RB(4,I)=S(5,I)/S(4,I)
001167          RB(5,I)=SQRT(S(7,I)/S(6,I))
001177          RB(6,I)=(S(9,I)/S(8,I))**2
001206     15   CONTINUE
001210          RB(2,3)=((S(5,1)+S(5,2))/(S(1,1)+S(1,2)))**.3333333333
001217          RB(3,3)=SQRT((S(5,1)+S(5,2))/(S(3,1)+S(3,2)))
001226          RB(4,3)=(S(5,1)+S(5,2))/(S(4,1)+S(4,2))
001232          RB(5,3)=SQRT((S(7,1)+S(7,2))/(S(6,1)+S(6,2)))
```

```
      RB(6,3)=((S(9,1)+S(9,2))/(S(8,1)+S(8,2)))**2
C
      RANE=RAN/ETA
      XL(1)=RVAP1*RANE
      XL(2)=RVAP2*RANE
      XL(3)=RVAP *RANE
      DO 17 I=1,2
      N=NSET(I)
      DO 17 K=1,6
      CALL LNGRIN(RB(K,I),DVB(K,I),RS,VDOUT,DYDX,N)
   17 CONTINUE
      DO 18 K=1,6
      DVB(K,3)=(ABS(DVB(K,1))*(1.-FVAP1)*EMDOT(1)+
     1         ABS(DVB(K,2))*(1.-FVAP2)*EMDOT(2))/
     2        ((1.-FVAP1)*EMDOT(1)+(1.-FVAP2)*EMDOT(2))
   18 CONTINUE
      DO 19 I=1,3
      DO 19 K=1,6
   19 RED(K,I)=RB(K,I)*REC
      DC=.375*RANE*ETA/AX
      DRAG(1) = S(10,1)* DC
      DRAG(2) = S(10,2)* DC
      DRAG(3) =  (S(10,1)+ S(10,2)) * DC
C
      GO TO 4
   20 AU(JZ-1,82) = RED(6,1)
      AU(JZ-1,83) = RED(6,2)
      AU(JZ-1,84) = RED(6,3)
      AU(JZ-1,85) = RLCOMB
      AU(JZ-1,86) = XL(3)
      AU(JZ-1,87) = ABS(DVB(6,1))
      AU(JZ-1,88) = ABS(DVB(6,2))
      AU(JZ-1,89) = ABS(DVB(6,3))
    4 CONTINUE
C
      IF (ILLIT) GO TO 62
      WRITE (6,90)
   90 FORMAT(1H0,///8X,6HRADIUS,15X,8HOXIDIZER,22X,4HFUEL,26X,5HTOTAL ,/
     1 24X,1HR,8X,2HDV,8X,3HRED,8X,1HR,8X,2HDV,8X,3HRED,8X,1HR,8X,
     2 2HDV,8X,3HRED,//)
      WRITE (6,91) ((RB(K,I),DVB(K,I),RED(K,I),I = 1,3),K =1,6)
   91 FORMAT(20H MASS MEAN DROP      ,3(3PF10.4,0PF10.4,F10.1),//,
     1        20H VOL. MEAN DROP      ,3(3PF10.4,0PF10.4,F10.1),//,
     2        20H VOL. DIAM. MEAN     ,3(3PF10.4,0PF10.4,F10.1),//,
     3        20H VOL. SURFACE MEAN   ,3(3PF10.4,0PF10.4,F10.1),//,
     4        20H MASS LOSS MEAN      ,3(3PF10.4,0PF10.4,F10.1),//,
     5        20H STABILITY MEAN      ,3(3PF10.4,0PF10.4,F10.1),// )
      WRITE (6,92) (XL(I),I=1,3),RLCOMB,(DRAG(I),I=1,3)
   92 FORMAT(///,31X,8HOXIDIZER,4X,4HFUEL,5X,5HTOTAL,4X,8HCOMBUST,,/
     1 ,23H BURNING RATE PARAMETER,7X,4F10.6,/
     2 ,15H DRAG PARAMETER,15X,3F10.2,/)
      WRITE(6,55)DX
   55 FORMAT(18H0INTEGRATION STEP=F7.4)
C
   62 DA=RAN/RHO3/SDSPD/AX/.592
      DAOX=DA*EMDOT(1)*RVAP1
      DAFU=DA*EMDOT(2)*RVAP2
      DATOT=DA*(EMDOT(1)+EMDOT(2))*RVAP
```

```
001474          DACO=DA*(EMDOT(1)+EMDOT(2))*RCOMB
001477          BROX=RAN*RVAR1*EMDOT(1)/AX        *1,4389/1,0601
001503          BRFU=RAN*RVAR2*EMDOT(2)/AX        *1,4389/1,0601
001506          BRTO=RAN*RVAR *(EMDOT(1)+EMDOT(2))/AX*1,4389/1,0601
001514          BRCO=RAN*RCOMB*(EMDOT(1)+EMDOT(2))/AX*1,4389/1,0601
001521          IF (ILLIT) GO TO 63
001523          WRITE(6,93) DAOX,DAFU,DATOT,DACO,BROX,BRFU,BRTO,BRCO
001546    93    FORMAT(///,30X,4F10,2,/)
001546       63 RETURN
001547           END
```

```
                  SUBROUTINE PROP(NSP)
000003            COMMON /E/FE,NM/B/BD/C/TA
000003            DIMENSION  FC(80), NM(20), BD(10, 20, 12),TA(1000)
000003            EQUIVALENCE  (TA(30), P), (TA(257), RAT),  ( TA(265), TSTG)
               1, (TA(264), TG), (TA(266),PO), (TA(267), VIS), (TA(268), FKG)
               2, (TA(269), CPG), (TA(399), RHOVS), (TA(483), WTML)
               3, (TA(484), RHOG),(TA(485), EMACH), (TA(486),SDSPD),(TA(259),GAM1)
               4, (TA(260),GAM2),(TA(261),GAM3),(TA(262),GAM4),(TA(263),GAM5)
               5,(TA(25),R), (TA(27), G), (TA(478), U)
         C
         C      ****************************************************************
         C
         C      ***** OBTAIN STAGNATION TEMP,TSTG, AND THE DERIVATIVE OF TEMP
         C      WITH RESPECT TO O/F, TGOD
         C
000003              CALL TGINT (RAT,P,TSTG,TGOD)
         C
         C      ***** OBTAIN MOLECULAR WEIGHT OF PRODUCTS AS FUNCTION  O/F
000006              CALL WTMINT (RAT,P,WTML,WTMLDT)
         C
000011          RG=R/WTML
000013              GAM =  FGAM(RAT)
000016          GAM1=GAM-1.
000020          GAM2=GAM1/2.
000022          GAM3=GAM2/GAM
000024          GAM4=GAM1/GAM
000025          GAM5 = GAM/GAM1
000027          U2=U*U
         C      ***** CALCULATE STATIC TEMP, FROM TOTAL TEMP, AND GAMMA
000030          TG=TSTG*(1.-GAM3*U2/RG/TSTG/G)
         C
         C
         C
         C      ***** CALCULATE GAS DENSITY
000036          RHOG=P/RG/TG
         C
         C
         C      ***** CALCULATE VISCOSITY, THERMAL CONDUCTIVITY, AND SPECIFIC HEAT
         C      OF GAS AS FUNCTION OF P, TG, O/F
000041              CALL VISGAS (RAT,P,TG,VIS,FKG,CPG,NSP)
         C
000050          RHOVS=RHOG/VIS 2.
000053          RHOTE=.375*RHOG
         C
         C      CALCULATE TOTAL PRESSURE
000054          PO = P*(TSTG/TG)**GAM5
000062          RR = RG * TG
000064          SDSPD = SQRT(RR * GAM * G)
000071          EMACH=U/SDSPD
000072          IF(EMACH .GT. 1.0) STOP
000077          EMACH2 = EMACH**2
         C
000101               RETURN
000101               END
```

```
               SUBROUTINE REED
000002         DIMENSION  FC(80), NM(20), BD(10,20,12),TA(1000),TITLE(24)
000002         COMMON /NLN/ LINES, LNS
000002         COMMON /E/ FC,NM /B/BD /C/TA
000002         COMMON / ADDPRM / PAR1, PAR2, PAR3, PAR4, PAR5, PAR6
000002         COMMON /PRNT/ KPRINT
000002         COMMON /PRPS/ PRPSYS(4) /SPEC/ NSP, SPNAME(2, 15) /OF/ R(15), NR
              1/DTL/ NTL(2) /DTFLM/ NTFLM(2) /BT/ NT /PRSSR/ PRSS(3) /CMPTAB/ VSP
              2(15, 15, 3) /WTM/ WMTAR(15, 3) /TGI/TC1(15, 3) /TBFGAM/ FGAMT(15)
              3/TABT/ TTAB(15) /VKSGS/ VSP(15, 15), CPTAB(15, 15) /MW/ WM(15)
              4/DIFFUS/ EPSI(15, 2), SIGMA(15, 2), EPSOF(2), SIGOF(2) /TLX/ TL(15
              5, 2) /PVY/ PV(15, 2) /RHOY/ RHOL (15, 2) /CPY/ CP(15, 2) /LAMY/
              6LAM(15, 2) /TFLMX/ TFILM(15, 2) /VISCVY/ VVIS(15, 2) /KVAPY/ KVAP
              7(15, 2) /CPVPY/ CPVAP(15, 2) /LINKA/ LOOSE
000002         EQUIVALENCE (TA(1), TITLE(1)), (TA(25),RR),  (TA(26), TWOPI)
              1,  (TA(27), G),   (TA(28), FTPI),  (TA(29), THRD), (FC(1), T)
              2,  (FC( 6), HMAX) , (FC(8),EMIN),  (FC(9),EMAX), (FC(14),TSTOP)
              3,  (NM(7), NSW) , (NM(9), MP), (NM(11), NO) , (NM(10),NV)
              4,  (TA(30), P) , (TA(31), RATMN), (TA(32),RATMX), (TA(33),AXMIN)
              5,  (TA(34), AXMAX), (TA(35), OFSTOC) ,(TA(38), V) ,(TA(36),EMDOT)
              6,  (TA(40),TLL) , (TA(42), RM ), (TA(44), SIG), (TA(46), NSET)
              7,  (TA(48), WTMOL), (FC(11), W) ,(TA(478), U) ,(TA(482),GJR)
              8,  (NM(15),NPLOT)
000002          DIMENSION   V(2),EMDOT(2),TLL(2) ,  RM(2), SIG(2), NSET(2)
              1, WTMOL(2) , W(3)
000002         RR= 18540,
000004         TWOPI = 6,2881853
000005         G = 386,4
000007         FTPI = 4,1887902
000010         THRD = ,33338333
000012         GJR = 9,78E-10
000013         READ (5, 1) (TITLE(I), I = 1, 24)
000025       1 FORMAT (10A6)
000025         WRITE (6, 700) (TITLE(I), I = 1, 24)
000037     700 FORMAT (1H1,10A6/ (1X10A6))
000037             READ(5,5 )  T, HMAX, EMIN, EMAX, TSTOP, U
000057       5     FORMAT (7E10,6)
000057             READ (5,8)  NSW, MP, NO, NPLOT, KPRINT
000075       8     FORMAT(6I10)
000075             READ (5,9)  P, RATMN, RATMX,  AXMIN, AXMAX, OFSTOC
000115             READ (5,9) (EMDOT(I), V(I),TLL(I), RM(I),SIG(I),NSET(I),I=1,2)
000146       9  FORMAT(5E10,6,I10)
000146         READ (5, 6000) PAR1, PAR2, PAR3  PAR4, PAR5, PAR6
000166    6000 FORMAT (6F9,0)
000166                W(1) = 1,0
000170                W(2) = 1,0
000171                W(3) = 1,0
000172            NM(13)=1
000173            NM(12)=1
000174            NM(14)=1
000175         WRITE (6, 602) PRPSYS
000202     602 FORMAT (16H0INPUT FOR OX = 2A6, 9H, FUEL = 2A6/)
000202         WRITE (6, 70) NR, NSP, NTL, NTFLM, NT
000220      70 FORMAT (                        24H NUMBER OF O/F RATIOS = I2/ 21H NUM
              1BER OF SPECIES = I2/ 38H NUMBER OF LIQUID TEMPERATURES (OX) = I2/
              240H NUMBER OF LIQUID TEMPERATURES (FUEL) = I2/ 36H NUMBER OF FILM
              3TEMPERATURES (OX) = I2/ 38H NUMBER OF FILM TEMPERATURES (FUEL) = I
```

```
                 42/ 36H NUMBER OF GAS PHASE TEMPERATURES = I2/)
000220                LINES = 14
000221                NTL1 = NTL(1)
000223                NTL2 = NTL(2)
000224                NTFLM1 = NTFLM(1)
000226                NTFLM2 = NTFLM(2)
000227                WRITE (6, 701)
000233           701 FORMAT (11H O/F RATIOS/)
000233                WRITE (6, 702) (R(I), I = 1, NR)
000246           702 FORMAT (12X6E20.8)
000246                IF (NR .GT. 12) LNS = 5
000252                IF (NR .LE. 12) LNS = 4
000255                IF (NR .LE. 6) LNS = 3
000260                LINES = LINES + LNS
000262                DO  15  IND=1,3
000263                WRITE (6, 703) IND, PRSS (IND)
000273           703 FORMAT (4H0PC(I1, 4H) = E15.8, 5H PSIA/)
000273                LINES = LINES + 3
000275                IF (LINES .GE. 50) WRITE (6, 704)
000303           704 FORMAT (1H1)
000303                IF (LINES .GE. 50) LINES = 0
000307                WRITE (6, 705)
000313           705 FORMAT (23H SPECIES MOLE FRACTIONS/)
000313                LINES = LINES + 1
000315                IF (LINES .GE. 50) WRITE (6, 704)
000323                IF (LINES .GE. 50) LINES = 0
000327                DO 12 I=1,NSP
000331                WRITE (6, 7020) SPNAME(1, I), SPNAME(2, I), (YSP(J, I, IND), J = 1
                 1, NR)
000356          7020 FORMAT (1H02A6, E19.8, 5E20.8/ (12X6E20.8))
000356                IF (NR .GT. 12) LNS = 4
000362                IF (NR .LE. 12) LNS = 3
000365                IF (NR .LE.  6) LNS = 2
000370                LINES = LINES + LNS
000372                IF (LINES .GE. 50) WRITE (6, 704)
000400            12 IF (LINES .GE. 50) LINES = 0
000407                WRITE (6, 706)
000412           706 FORMAT (18H0AVE. GAS MOL. WT./)
000412                WRITE (6, 702) (WMTAB(I, IND), I = 1, NR)
000427                CALL PAGER(NR)
000431                WRITE (6, 707)
000435           707 FORMAT (32H0EQUILIBRIUM GAS TEMP. (RANKINE)/)
000435                WRITE (6, 702) (TC1(I, IND), I = 1, NR)
000452            15 CALL PAGER(NR)
000454                WRITE (6, 708)
000462           708 FORMAT (6H0GAMMA/)
000462                WRITE (6, 702) (FGAMT(J), J = 1, NR)
000475                CALL PAGER(NR)
000477                WRITE (6, 709)
000503           709 FORMAT (26H0GAS PHASE TEMP. (RANKINE)/)
000503                WRITE (6, 702) (TTAB(I), I = 1, NT)
000516                CALL PAGER(NT)
000520                WRITE (6, 710)
000524           710 FORMAT (51H0GAS PHASE VISC. ((LBS MASS / IN - SEC) X 10 ** +6)/)
000524                LINES = LINES + 3
000526                IF (LINES .GE. 50) WRITE (6, 704)
000534                IF (LINES .GE. 50) LINES = 0
000540                DO 17 I=1,NSP
```

```
000542          WRITE (5, 702) (VSP(J, I), J = 1, NT)
000556       17 CALL PGR(NT)
000563          WRITE (5, 711)
000564      711 FORMAT (34H0GAS PHASE CP (BTU / MOLE * DEG R)/)
000566          LINES = LINES + 3
000570          IF (LINES .GE. 50) WRITE (6, 704)
000576          IF (LINES .GE. 50) LINES = 0
000602          DO 19 I=1,NSP
000604          WRITE (5, 702) (CPTAB(J, I), J = 1, NT)
000620       19 CALL PGR(NT)
000625          WRITE (5, 712)
000630      712 FORMAT (17H0SPECIES MOL. WT./)
000630          WRITE (5, 702) (WM(I), I = 1, NSP)
000643          CALL PAGER(NSP)
000645          WRITE (5, 713)
000651      713 FORMAT (35H0SPECIES INTERACTION ENERGY (DEG K)/)
000651          WRITE (5, 702) (EPSI(I, 1), I = 1, NSP)
000664          CALL PAGER(NSP)
000666          WRITE (5, 714)
000672      714 FORMAT (33H0PROP. INTERACTION ENERGY (DEG K)/)
000672          WRITE (5, 702) EPSOF
000700          CALL PAGER(2)
000702          WRITE (5, 715)
000706      715 FORMAT (30H0SPECIES MOL. DIA. (ANGSTROMS)/)
000706          WRITE (5, 702) (SIGMA(I, 1), I = 1, NSP)
000721          CALL PAGER(NSP)
000723          WRITE (5, 716)
000727      716 FORMAT (28H0PROP. MOL. DIA. (ANGSTROMS)/)
000727          WRITE (5, 702) SIGOF
000735          CALL PAGER(2)
000737          WRITE (5, 717)
000743      717 FORMAT (15H0PROP. MOL. WT./)
000743          WRITE (5, 702) WTMOL
000751          CALL PAGER(2)
000753          WRITE (5, 718)
000757      718 FORMAT (25H00X, LIQ. TEMP. (RANKINE)/)
000757          WRITE (5, 702) (TL(J, 1), J = 1, NTL1)
000772          CALL PAGER(NTL1)
000774          WRITE (5, 720)
001000      720 FORMAT (25H00X, VAPOUR PRESS. (PSIA)/)
001000          WRITE (5, 702) (PV(J, 1), J = 1, NTL1)
001013          CALL PAGER(NTL1)
001015          WRITE (5, 722)
001021      722 FORMAT (38H00X, LIQ. DENSITY (LBS MASS / CU INCH)/)
001021          WRITE (5, 702) (RHOL(J, 1), J = 1, NTL1)
001034          CALL PAGER(NTL1)
001036          WRITE (5, 724)
001042      724 FORMAT (36H00X, LIQ. CP (BTU / LB MASS - DEG R)/)
001042          WRITE (5, 702) (CP(J, 1), J = 1, NTL1)
001055          CALL PAGER (NTL1)
001057          WRITE (5, 726)
001063      726 FORMAT (33H00X. HEAT OF VAP. (BTU / LB MASS)/)
001063          WRITE (5, 702) (LAM(J, 1), J = 1, NTL1)
001076          CALL PAGER(NTL1)
001100          WRITE (5, 719)
001104      719 FORMAT (26H0FUEL LIQ. TEMP. (RANKINE)/)
001104          WRITE (5, 702) (TL(J, 2), J = 1, NTL2)
001117          CALL PAGER(NTL2)
```

```
001121           WRITE (5, 721)
001125       721 FORMAT (20H0FUEL VAPOUR PRESS, (PSIA)/)
001125           WRITE (5, 702) (PV(J, 2), J = 1, NTL2)
001140           CALL PAGER(NTL2)
001142           WRITE (6, 723)
001146       723 FORMAT (39H0FUEL LIQ, DENSITY (LBS MASS / CU INCH)/)
001146           WRITE (5, 702) (RHOL(J, 2), J = 1, NTL2)
001161           CALL PAGER(NTL2)
001163           WRITE (5, 725)
001167       725 FORMAT (37H0FUEL LIQ, CP (BTU / LB MASS - DEG R)/)
001167           WRITE (5, 702) (CP(J, 2), J = 1, NTL2)
001202           CALL PAGER(NTL2)
001204           WRITE (5, 727)
001210       727 FORMAT (34H0FUEL HEAT OF VAP, (BTU / LB MASS)/)
001210           WRITE (5, 702) (LAM(J, 2), J = 1, NTL2)
001223           CALL PAGER(NTL2)
001225           WRITE (6, 728)
001231       728 FORMAT (27H00X, VAPOUR TEMP, (RANKINE)/)
001231           WRITE (5, 702) (TFILM(J, 1), J = 1, NTFLM1)
001244           CALL PAGER(NTFLM1)
001246           WRITE (5, 730)
001252       730 FORMAT (52H00X, VAPOUR VISC, ((LBS MASS / IN - SEC) X 10 ** +6)/)
001252           WRITE (5, 702) (VVIS(J, 1), J = 1, NTFLM1)
001265           CALL PAGER (NTFLM1)
001267           WRITE (5, 732)
001273       732 FORMAT (62H00X, VAPOUR CONDUCTIVITY ((BTU / IN - SEC - DEG R) X 10
                1 ** +6)/)
001273           WRITE (5, 702) (KVAP(J, 1), J = 1, NTFLM1)
001306           CALL PAGER(NTFLM1)
001310           WRITE (5, 734)
001314       734 FORMAT (38H00X, VAPOUR CP (BTU / LB MASS - DEG R)/)
001314           WRITE (5, 702) (CPVAP(J, 1), J = 1, NTFLM1)
001327           CALL PAGER(NTFLM1)
001331           WRITE (5, 729)
001335       729 FORMAT (28H0FUEL VAPOUR TEMP, (RANKINE)/)
001335           WRITE (5, 702) (TFILM(J, 2), J = 1, NTFLM2)
001350           CALL PAGER(NTFLM2)
001352           WRITE (5, 731)
001356       731 FORMAT (53H0FUEL VAPOUR VISC, ((LBS MASS / IN - SEC) X 10 ** +6)/)
001356           WRITE (5, 702) (VVIS(J, 2), J = 1, NTFLM2)
001371           CALL PAGER(NTFLM2)
001373           WRITE (5, 733)
001377       733 FORMAT (63H0FUEL VAPOUR CONDUCTIVITY ((BTU / IN - SEC - DEG R) X 1
                10 ** +6)/)
001377           WRITE (5, 702) (KVAP(J, 2), J = 1, NTFLM2)
001412           CALL PAGER(NTFLM2)
001414           WRITE (5, 735)
001420       735 FORMAT (39H0FUEL VAPOUR CP (BTU / LB MASS - DEG R)/)
001420           WRITE (5, 702) (CPVAP(J, 2), J = 1, NTFLM2)
001433           CALL PAGER(NTFLM2)
001435           IF (LOOSE .EQ. 0) WRITE (6, 736)
001442           IF (LOOSE .EQ. 1) WRITE (6, 737)
001450       736 FORMAT (24H0NO FUEL THERMAL DECOMP,)
001450       737 FORMAT (21H0FUEL THERMAL DECOMP,)
001450        16 WRITE (5, 20) (TITLE(I), I = 1, 24)
001462        20 FORMAT (44H1ISN7002 STEADY-STATE SPRAY COMBUSTION MODEL/(1H,10A6))
001462           WRITE(5,40)(EMDOT(I),RM(I),SIG(I),WTMOL(I),               I=1,2)
001505        40 FORMAT(1H0
```

```
         1 6X     50H MASS FLOW    RM          SIG  MOLE WT
           12H O           F15.2,   E12.3,   2F7.2          /
           22H F           F15.2,   E12.3,   2F7.2          )
001505     WRITE (5, 30) MP
001513   50 FORMAT (1940HMAX / HMIN = 2 **, I2)
001513           RETURN
001514           END


              SUBROUTINE RSET
000002     DIMENSION  FC(80), NM(20), RD(10, 20, 12), TA(1000),FA(2),ENMP(2)
000002     COMMON  /E/ FC, NM /H/ RD /C/TA
000002     EQUIVALENCE  (NM(14), IRZ) ,(NM(12), JZ), (TA(50), FA)
         1,(TA(479), ENMP),(TA(481), PHI),(TA(258),EMD),(TA(36), EMDOT)
         2,(TA(52), DNT ), (TA(54), WCON), (TA(42), RM), (TA(44),SIG)
         3,(TA(46), NSET), (TA(40),TTL), (TA(38), VV) ,(RD(801), TL)
         4,(RD(1601), V) , (RD(1), EM) , (TA(56), EMINT),(TA(96),RS)
         5,(TA(136), DN), (TA(176), KK) , (TA(216),WW),(TA(25), R)
         6, (TA(257), RAT), (TA(256), DNTT),(TA(48),WTMOL)
         7, (TA(31),RATMN),(TA(32),RATMX)
000002     DIMENSION  EMDOT(2), DNT(2), WCON(2), RM(2), SIG(2), NSET(2)
         1,  TTL(2), VV(2), EMS(20), DNS(20), RSS(20), TL(10,20,2),WW(20,2)
         2, KK(20,2), RS(20,2), DN(20,2),  EMINT(20,2),EM(10,20,2)
         3, V(10,20,2) ,WTMOL(2)
000002       IRZ = 0
000003       JZ  = 1
000004       PHI = 0.0
000005       EMD = EMDOT(1) + EMDOT(2)
000007         DO 100 I= 1,2
000011     FA(I) = EMDOT(I)
000014         ENMP(I)= 0.0
000016         DNT(I) = 0.0
000020         WCON(I) = 6.2831853* WTMOL(I)/ R
000024         N  =  NSET(I)
000026     CALL LOGNRM(RM(I),SIG(I),N,RSS)
000032     CALL MASSET(EMS,RHO(TTL(I ),I),RSS,EMDOT(I),N,DNS)
000043     NSET(I) = N+4
000046     N = NSET(I)
000050     DO 100 J=1,N
000052         TL(1,J,I) = TTL(I)
000060         V(1,J,I)  = VV(I)
000066         EM(1,J,I) = EMS(J)
000074         EMINT (J,I)=  EMS(J)
000101         RS(J,I)      =  RSS(J)
000104         DN(J,I)      =  DNS(J)
000113         DNT(I)    =   DNT(I) +   DNS(J)
000117         KK(J,I)   =   1
000123         WW(J,I)   =   0.0
000127   100       CONTINUE
000133         DNTT =     DNT(1)   + DNT(2)
000135         RAT   =   EMDOT(1)/EMDOT(2)
000137     RAT=AMIN1(RATMX,AMAX1(RATMN,RAT))
000146         RETURN
000146         END
```

```
                FUNCTION RT(RS)
          C     CALCULATES DISTANCE OF DISSOCIATION FLAME AS FUNCTION OF RADIUS
000003          DIMENSION RRB(5),RRT(5)
000003          DATA RRS, RRT/ 0., 100., 200., 300., 500., 8., 13., 17., 18., 18./
          C     CONVERT RS(K) TO MICRONS
000003          RST = RS
000004          RST =RST * 2,54E+4
000006          CALL LV3RIN  (RST,RT,RRS,RRT,DRTDRS,5)
000012          RT = RT / 2,54E+4
000014          RETURN
000014          END
```

```
                SUBROUTINE SHIFT
000002             DIMENSION  FC(80), NM(20), BD(2400),NST(2),NED(2)
000002           COMMON /F/ FC, NM /B/ BD
000002          EQUIVALENCE (NM(5),MPTN),(NM(4),MGAM), (NM(3),MALP),
               1 (NM(1),IM), (FC(3),H), (FC(7),HZD2), (NM(10),NV), (FC(4),HO),
               2 (FC(1),T), (NM(2), INDR), (FC(10), F1), (NM(8),NCOU),
               3 (FC(6), HMAX), (NM(6),MPTS), (FC(5),HMIN), (FC(9), FMAX),
               4  (FC(2),RKT) ,(NM(17),NST),(NM(19),NED)
          C      ***************************************************************
          C      SHIFT UPDATES THE VARIABLES SO THAT PROPER POSITIONING
          C      OCCURS DURING THE PROPER CYCLE
          C      ***************************************************************
000002          IF ( MPTN) 15, 10, 15
000003       10  MPTN = MPTS
000005       15  MGAM = -MGAM
000006          IF( MGAM ) 80, 20, 60
000010       20  IF( MALP - 2) 25, 48, 48
000013       25  IM = IM + 1
000015          MPTN = MPTN - 1
000016          NCOU =  NCOU + 1
000020          IF( 3 - IM)  35, 30, 30
000022       30  MALP = 4
000023          H = HZD2
000025          GO TO 40
000025       35  MGAM = -1
000026       40 DO 42 J=1,5
000030            DO 42 KL = 1,2
000031            LS = NST(KL) + 400*(J-1)
000036            LE = NED(KL) + 400*(J-1)
000044              DO 42 I = LS,LE,10
000046                     BD(I+1) = BD(I+3)
000050                     BD(I+2) = BD(I+4)
000051                     BD(I+3) = BD(I+5)
000053                     BD(I+4) = BD(I+6)
000054                     BD(I+5) = BD(I+7)
000054       42            BD(I   ) = BD(I+9)
000066          RETURN
          C      ***************************************************************
          C      SHIFTING OCCURS AFTER PREDICTOR CYCLE IS COMPLETE
          C      ***************************************************************
000066       48 MALP = MALP - 1
000070          IF( MALP - 2) 55, 50, 55
000072       50 H = HO
000074          GO TO 65
000074       55 T = T + HZD2
000076          GO TO 65
000077       60  T  = T + H
000101       65 DO 75 J = 1,6
000103            DO 75 KL = 1,2
000104            LS = NST(KL) + 400*(J-1)
000111            LE = NED(KL) + 400*(J-1)
000117              DO 75 I=LS,LE,10
000121            BD(I+8) = BD(I+7)
000123            BD(I+7) = BD(I+6)
000124            BD(I+6) = BD(I+5)
000126            BD(I+5) = BD(I+4)
000127            BD(I+4) = BD(I+3)
```

```
000131          BD(I+3) = BD(I+2)
000132          BD(I+2) = BD(I+1)
000134          BD(I+1) = BD(I   )
000136       95 BD(I   ) = BD(I+9)
000146          RETURN
        C       ****************************************************************
        C       THE FOLLOWING STATEMENTS EXIST FOR CHANGING THE STEP SIZE
        C       ****************************************************************
000146      50 IF(INDR) 175, 135, 124
000150     124 IM = -1
000151     125 MPTN = MPTN + 1
000153     130  IM = IM + 1
000155         INDR = 0
000156         E1 = 0.0
000157         NCOU = NCOU + 1
000160         RETURN
        C       ****************************************************************
        C       DOUBLE THE INTERVAL IF POSSIBLE
        C       ****************************************************************
000161     135 IF(IM - 8) 185, 140, 140
000164     140  KZ = MPTN/2
000166         IF(2*KZ - MPTN) 150, 125, 150
        C       ****************************************************************
        C       IF MPTN IS ODD THERE IS AN EVEN NUMBER OF POINTS LEFT TO COMPUTE
        C       ****************************************************************
000167     150  IF((H-HMAX)/HMAX) 155, 125, 125
000172     155 IF(MPTS - 1) 125, 125, 160
000175     160  MPTS = MPTS/2
000177         MPTN = MPTN/2
000200          IM = 5
000201         DO 165 J = 1,6
000202          DO 165 KL=1,2
000203          LS = NST(KL) + 400*(J-1)
000210          LE = NED(KL) + 400*(J-1)
000216            DO 165 I = LS,LE,10
000220            BD(I+1) = BD(I+2)
000222            BD(I+2) = BD(I+4)
000223            BD(I+3) = BD(I+6)
000225     165    BD(I+4) = BD(I+8)
000234         H = 2.*H
000236         GO TO 130
        C       ****************************************************************
        C       HALF THE STEP SIZE  IF POSSIBLE
        C       ****************************************************************
000236     175 IF((H-HMIN)/HMIN) 124, 124, 180
000241     180 N = ALOG(E1/EMAX  + 1.)/.6931471805
000250          DO 185 I = 1,N
000252         K = I
000253          IF(H/2.**K - HMIN) 195, 190, 185
000262     185  CONTINUE
000265     190  N = K
000267         GO TO 200
000267     195  N = K -1
000271     200   MALP = 4
000272         MGAM = 0
000273         IF( IM - 4) 210, 215, 210
000275     210  T = T+4
000277         RKT = T
```

```
000300          NN = 1
000301          GO TO 216
000302     215  T = RKT
000304           MPTN = MPTN + 4
000305          NN=5
000306     216  MPTS=MPTS*2**,
000313          MPTN=MPTN*2**N
000320          DO 222 J = 1,6
000322           DO 222 KL=1,2
000323           LS = NST(KL) + 400*(J-1)
000330           LF = NED(KL) + 400*(J-1)
000336             DO 222 I = LS,LF,10
000340             K = I + NN
000342     222     ED(I) = HD(K)
000353          HO = H/2.**N
000357          H2O2 = HO/2.
000361          H = H2O2
000362          IM = 0
000362          INDR = 0
000363          RETURN
000364           END
```

```
                 SUBROUTINE SUM
000002          DIMENSION    NSET(2),ENMP(2), DN(20,2),DM(10,20,2),FA(2),
              1 EM(10,20,2), V(10,20,2), DV(10,20,2), TL(10,20,2) RS(20,2),
              2  VD(20,2), DNT(2),BD(10,20,12),TA(1000),FC(80),NM(20)
              3,DT(10,20,2)   ,EMDOT(2)
              4, EMINT(20,2)
000002          EQUIVALENCE (TA(46),NSET), (TA(479),ENMP)  (TA(136),DN),
              1  (BD(401),DM), (BD(1),EM), (BD(1601),V), (BD(2001),DV),
              2 (TA(50),FA), (TA(478), U), (FC(3),DX), (BD(801), TL),
              3  (TA(95),RS), (TA(311), VD), (TA(52), DNT), (FC(1),X),
              4 (TA(484),RHOG), (TA(27),G), (TA(30),P),(TA(257),RAT), (TA(9
              5 RATP),(TA(31),RATMN), (TA(32), RATMX)
              6,(BD(1201), DT) ,(TA(36), EMDOT)
              7, (TA(55),EMINT)
000002          COMMON /E/FC,NM /H/HD/C/TA
000002          ENMP(1) = 0.
000003          ENMP(2) = 0.
000004          SUMP = 0.
000005          SUMPA = 0.
000006             DO 200 I = 1,2
000007           FA(I) = EMDOT(I)
000012            N = NSET(I)
000014           DO 200 J =1,N
000016          IF(EM(1,J,I) .GT. .01*EMINT(J,I)) GO TO 20
000030     10    EM(1,J,I) = 0.0
000036           TL(1,J,I) = 0.0
000043           V(1,J,I) = 0.0
000050             EM(10,J,I) = 0.0
000056             TL(10,J,I) = 0.0
000062             V (10,J,I) = 0.0
000067             DM(10,J,I) = 0.0
000074             DT(10,J,I) = 0.
```

```
000101             DV(10,J,I) = 0,0
000106             DV( 1,J,I) = 0,0
000115             DM( 1,J,I) = 0,0
000120             DT( 1,J,I) = 0,0
000125             NM(I+16) = J*10+1+200*(I-1)
000134          RS(J,I) = 0,
000137          VD(J,I) = 0,
000143          DNT(I) = DNT(I) - DN(J,I)
000150          DN(J,I) = 0,
000154       20 CONTINUE
000154          ENMP(I) = ENMP(I) + DN(J,I) * DM(1,J,I)
000166          SUMP = SUMP + DN(J,I) * DM(1,J,I) * (V(1,J,I)-U) * DX
000207          SUMPA = SUMPA + DV(1,J,I) * EM(1,J,I) *  DN(J,I) * DX
000222          FA(I) = FA(I) - DN(J,I) * EM(1,J,I)
000233          FA(I)=AMAX1(FA(I),0,49E-10)
000240      200 CONTINUE
000244          AX = A(X)
000246          A1 = AX - AP(X) * DX
000252          A2 = AX
000253          A1DA2 = A1/A2
000255          PHIP = -(ENMP(1) + ENMP(2))
000257          PHI = FA(1) + FA(2)
000261          U = PHI / RHOG / AX
000264          P1 = U * (-PHIP) * DX / (G*A2)
000271          P2 = -SUMP / (G*A2)

000273          P3 = -SUMPA / (G*A2)
000275          P4 = -RHOG * U**2 * (A1/A2 -1,0)/G
000303          P = P1+P2+P3+P4    +P
000310          RAT=EMDOT(1)/EMDOT(2)
000312          IF(FA(1)+FA(2) ,GT, 1,E-10) RAT=FA(1)/FA(2)
000317          RATP = (FA(1)/FA(2)*ENMP(2)-ENMP(1)) / FA(2)
000323          IF (RAT ,GE, RATMN) GO TO 1262
000325          RAT = RATMN
000326          RATP = 0,
000327     1262 IF (RAT ,LE, RATMX) GO TO 1264
000332          RAT = RATMX
000332          RATP = 0,
000333     1264 CONTINUE
000333          RETURN
000334          END
```

```
                SUBROUTINE TWFL(J,I)
000005          DIMENSION KK(20,2),KDISC(20,2),XENTR(20,2),WENTR(20,2),WW(20,2),
              1RS(20,2),TL(10,20,2),TWBINT(20,2), DELX(20,2),V(10,20,2),
              2 EM(10,20,2),DUMITL(20,2),DUMTL(20,2),DM(10,20,2),BETA(20,2),
              3FNUM(20,2),DT(10,20,2),FC(80),NM(20),BD(10,20,12),TA(1000)
000005          EQUIVALENCE (TA(176),KK),(TA(270),KDISC), (TA(689),XENTR),
              1(TA(729),WENTR), (TA(213),WW), (TA(96),RS),(BD(801),TL)
              1, (TA(769),TWBINT), (TA(809),DELX),(BD(1601),V),(BD(1),EM),
              3 (TA(849),DUMITL), (TA(889),DUMTL), (BD(401),DM), (TA(647),BETA),
              4 (TA(433),FNUM), (BD(1201),DT), (FC(1),X), (TA(26),TWOPI),
              5 (TA(473), CPA), (TA(474),FKAV), (FC(3),DX)
000005          COMMON/E/FC,NM/H/BD/C/TA
000005     163  II = KK(J,I)
000011          KDISC(J,I) = 1
000015          GO TO (164,165),II
000022     164  KK(J,I) = 2
000026          IF(X) 601, 601, 600
000030     600 XENTR(J,I) = X
000034         WENTR(J,I) = WW(J,I)
000043         XL = XK(RS(J,I))
000052         W = XL * TWOPI * RS(J,I) * RHO(TL(1,J,I),I)
000070         ZZ = W * CPA /FKAV * RT(RS(J,I)) /2. /TWOPI/RS(J,I)/RS(J,I)
000106         GO TO 602
000106     601 XENTR(J,I) = -.001
000112         XL = XK(RS(J,I))
000121         WENTR(J,I) = XL*TWOPI*RS(J,I)*RHO(TL(1,J,I),I)
000142         ZZ = WENTR(J,I) * CPA * RT(RS(J,I))/FKAV/2./TWOPI/RS(J,I)/RS(J,I)
000163     602 TWBINT(J,I) = 817.
000167         DELX(J,I) =V(1,J,I)*EM(1,J,I)*CPL(TL(1,J,I),I)* (TWBINT(J,I)-
             1 TL(1,J,I))/TWOPI/RS(J,I)/RHO(TL(1,J,I),I)/562./XL
000242         DUMITL(J,I) = TL(1,J,I)
000252         DUMTL (J,I) = TL(1,J,I)
000262     165 XL = XK(RS(J,I))
000271         W = XL * TWOPI * RS(J,I)*RHO(TL(1,J,I),I)
000307         ZZ = W * CPA /FKAV * RT(RS(J,I)) /2. /TWOPI/RS(J,I)/RS(J,I)
000325         TWB = 817.
000326          XTRA = XENTR(J,I) + DELX(J,I)
000335         IF(X-XTRA)166,167,167
000340     166 CONTINUE
000340         W = WENTR(J,I) + (W-WENTR(J,I)) / DELX(J,I) * (X-XENTR(J,I))
000360         TWB = DUMITL(J,I) + (TWB-DUMITL(J,I))/DELX(J,I)*(X-XENTR(J,I))
000377         DT(1,J,I) = (TWB-DUMTL(J,I))/DX
000411         DUMTL(J,I) = TWB
000415         DM(1,J,I) = -W/V(1,J,I)
000431         BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000444         WW(J,I) = W
000450         GO TO 156
000450     167 DM(1,J,I) = -W/V(1,J,I)
000464         DT(1,J,I) = (TWB-DUMTL(J,I))/DX
000475         DUMTL(J,I) = TWB
000501         BETA(J,I) = W/RS(J,I)/FNUM(J,I)
000514     156 RETURN
000515         END
```

```
                  SUBROUTINE VAPOR(J,I)
000005              COMMON /E/FB,NM/B/BD/C/TA
000005             DIMENSION  FB(80), NM(20) , BD(10,20,12) , TA(1000),WCON(2)
                  1 ,PE(2), BETA(20,2),RS(20,2), FNUM(20,2),M(10,20,2),DT(10,20,2)
                  2,FNUH(20,2),TL(10,20,2), EM(10,20,2), V(10,20,2)
                  3 ,DM(10,20,2), WW(20,2)
000005             EQUIVALENCE  (TA(257), RAT), (TA(30), P), (TA(54),WCON)
                  1,(TA(687), PE), (TA(473), DPOT), (TA(476),PA), (TA(647),BETA)
                  2,(TA( 96), RS), (TA(433), FNUM) , (BD(401),DM), (BD(1201), DT)
                  3,(TA(26), TWOPI), (TA(393),FNUH), (TA(474), FKAV), (TA(264), TG)
                  4,(BD(801), TL), (BD(1), EM),(BD(1601), V), (TA(475),CPA)
                  5,(TA(482), GJR), (TA(392),RV)
                  6, (TA(216),WW), (BD(401), DM)
000005                 PE(1) = 0,0
000006                 PE(2) = 0,0
000007                 BETA(J,I) = WCON(I)*DPOT*ALOG((P-PE(I))/(P-PA))
000025                 W  = BETA(J,I)*RS(J,I)*FNUM(J,I)
000040                 IF (W)  190, 192, 192
000041       190      W = 0,0
000042                 WRITE  (6, 2050)
000046      2050       FORMAT( 19HOW NEG, SET TO ZERO)
000046                 DM(1,J,I) = 0,0
000054                 DT(1,J,I) = TWOPI*FKAV*RS(J,I)*FNUH(J,I)/EM(1,J,I)*(TG -TL(1,
                  1J, I)) / CPL(TL(1, J, I), I) / V(1, J, I)
000125              WW(J, I) = W
000131                 RETURN
000132       192 DM(1, J, I) = -W / V(1, J, I)
000146              WW(J, I) = W
000152                 Z = W/TWOPI*CPA/RS(J,I)/FNUH(J,I)/FKAV
000164                 EX  = EXP (Z)-1,
000170              DIF= ALM(TL(1,J,I),I) - CPA*(TG- TL(1,J,I))/EX + GJR*(W/RV/RS(J,I)
                  1 /RS(J,I))**2
000220              CPLTL = CPL(TL(1, J, I), I)
000230       200 FORMAT (1H1)
000230                 DT(1,J,I) = -DIF/CPL(TL(1,J,I),I)/EM(1,J,I)*W/V(1,J,I)
000264                              IF(DT(1,J,I) + 100,)  7711, 156, 156
000273      7711       DT(1,J,I) =  -100,
000301       156                    RETURN
000302                              END
```

```
                   FUNCTION XK(RS)
            C      CALCULATES DISSOCIATION BURNING RATE CONSTANT AS FUNCTION OF
            C      RADIUS
000003             DIMENSION XXK(5),RRS(5)
000003             DATA XXK, RRS/ 3,2, 6,3, 7,3, 8,2, 11,, 0,, 100,, 200,, 300,, 500,
                  1/
            C      CONVERT RS(K) TO MICRONS
000003             RST = RS
000004             RST = RST * 2,54E+4
000006             CALL LNGRIN  (RST,XK,RRS,XXK,DXKDRS,5)
000012             XK = XK *1,E-3/2,54/2,54
000014             RETURN
000014             END
```

```
              SUBROUTINE PLOTY
000002        RETURN
000003        END
```

```
              SUBROUTINE COMP (OFR, P, Y, NSP)
        C     COMPOSITION OF COMBUSTION GASES AT ADIABATIC FLAME TEMPERATURE
        C     AS A FUNCTION OF      O/F RATIO, PRESSURE
000007        COMMON /CMPTAB/ YSP(15, 15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000007        DIMENSION Y(NSP), YSPB(15, 15)
000007        NS = NSP
000010        IF (P .LE. PRSS(2)) IND = 1
000013        IF (P .GT. PRSS(2)) IND = 2
000016        A = (P - PRSS(IND)) / (PRSS(IND + 1) - PRSS(IND))
000023        DO 1 J = 1, NR
000024        DO 1 I = 1, NS
000025      1 YSPB(J, I) = YSP(J, I, IND) + A * (YSP(J, I, IND +1)-YSP(J,I,IND))
000055        DO 2 I = 1, NS
000056      2 CALL LNGRIN (OFR, Y(I), R, YSPB(1, I), DYDX, NR)
000073        SUM = 0.
000074        DO 3 I = 1, NS
000075        IF (Y(I) .GE. 0.) GO TO 3
000077        Y(I) = 0.
000101      3 SUM = SUM + Y(I)
000106        DO 4 I = 1, NS
000110      4 Y(I) = Y(I) / SUM
000114          RETURN
000115          END
```

```
              FUNCTION TBL(P,I)
        C     BOILING TEMP OF OX(I = 1), FUEL(I = 2)
000005        COMMON /PVY/ PV(15, 2) /TLX/ TL (15, 2) /DTL/ NTL(2)
000005        CALL LNGRIN(P, TBL, PV(1, I), TL(1, I), DTBDPR, NTL(I))
000017        RETURN
000021        END
```

```
              FUNCTION VISCV(T,I)
        C     VAPOR VISCOSITY FOR OX(I = 1), FUEL(I = 2)
000005        COMMON /TFILMX/ TFILM(15, 2) /VISCVY/ VVIS(15, 2) /DTFLM/ NTFLM(2)
000005        CALL LNGRIN(T, VISCV, TFILM(1, I), VVIS(1, I), DVISDT, NTFLM(I))
000017         VISCV = VISCV*1.0E-6
000021        RETURN
000021        END
```

```
                FUNCTION RHO (T,I)
        C       LIQUID DENSITY OF OX(I = 1), FUEL(I = 2)
000005          COMMON /TLX/ TL(15, 2) /RHOY/ RHOL(15, 2) /DTL/ NTL(2)
000005          CALL LN3RIN(T, RHO, TL(1, I), RHOL(1, I), DRHODT, NTL(I))
000017          RETURN
000021          END
```

```
                FUNCTION PVAP (T,I)
        C       VAPOR PRESSURE OF OX(I = 1), FUEL(I = 2)
000005          COMMON /TLX/ TL(15, 2) /PVY/ PV(15, 2) /DTL/ NTL(2)
000005          CALL LN3RIN(T, PVAP, TL(1, I), PV(1, I), DPVDTL, NTL(I))
000017          RETURN
000021          END
```

```
                FUNCTION FKA (T,I)
        C       VAPOR THERMAL CONDUCTIVITY OF OX(I = 1), FUEL(I = 2)
000005          REAL KVAP
000005          COMMON /TFLMX/ TFILM(15, 2) /KVAPY/ KVAP(15, 2) /DTFLM/ NTFLM(2)
000005          CALL LN3RIN(T, FKA, TFILM(1, I), KVAP(1  I), DKVDTF, NTFLM(I))
000017          FKA=FKA*1.0E-06
000021          RETURN
000021          END
```

```
                FUNCTION CVAP (T,I)
        C       VAPOR SPECIFIC OF OX(I = 1), FUEL(I = 2)
000005          COMMON /TFLMX/ TFILM(15, 2) /CPVPY/ CPVAP(15, 2) /DTFLM/ NTFLM(2)
000005          CALL LN3RIN(T, CVAP, TFILM(1, I), CPVAP(1, I), DCVDT, NTFLM(I))
000017          RETURN
000021          END
```

```
                FUNCTION CPL (T,I)
        C       LIQUID SPECIFIC HEAT OF OX(I = 1), FUEL(I = 2)
000005          COMMON /TLX/ TL(15, 2) /CPY/ CP(15, 2) /DTL/ NTL(2)
000005          CALL LN3RIN(T, CPL, TL(1, I), CP(1, I), DCPDT, NTL(I))
000017          RETURN
000021          END
```

```
                FUNCTION ALM (T,I)
        C       HEAT OF VAPORIZATION OF OX(I = 1), FUEL(I = 2)
000005          REAL LAM
000005          COMMON /TLX/ TL(15, 2) /LAMY/ LAM(15, 2) /DTL/ NTL(2)
000005          CALL LN3RIN(T, ALM, TL(1, I), LAM(1, I), DALMDT, NTL(I))
000017          RETURN
000021          END
```

```
                 SUBROUTINE WTMINT (OFR,P,WM,DOFRWM)
        C        MOLECULAR WT OF COMBUSTION GASES AS A FUNCTION OF O/F RATIO
000007           COMMON /WTM/ WMTAB(15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000007           DIMENSION WMT(3)
000007           DO 1 I = 1, 3
000010         1 CALL LN3RIN(OFR, WMT(I), R, WMTAB(1, I), DWMDOF, NR)
000025           CALL LN3RIN(P, WM, PRSS, WMT, DOFRWM, 3)
000031           RETURN
000032           END
```

```
                 SUBROUTINE TGINT (OFR,PC,T,DTDOFR)
        C        ADIABATIC FLAME TEMPERATURE AS A FUNCTION OF O/F RATIO , PRESS.
000007           COMMON /TGI/ TC1(15, 3) /PRSSR/ PRSS(3) /OF/ R(15), NR
000007           DIMENSION TT(3)
000007           DO 1 I = 1, 3
000010         1 CALL LN3RIN(OFR, TT(I), R, TC1(1, I), DTCDOF, NR)
000025           CALL LN3RIN(PC, T, PRSS, TT, DTDOFR, 3)
000031           RETURN
000032           END
```

```
                SUBROUTINE VKSGAS (OFR, P, T, VISG, TKG, CPG, NSP)
         C        VISCOSITY,  THERMAL CONDUCTIVITY,  AND  SPECIFIC HEAT OF
         C        COMBUSTION  GASES AS A FUNCTION OF O/F RATIO, PRESSURE, AND
         C        TEMPERATURE
000012          COMMON /TABT/ TTAB(15) /VKSGS/ VSP(15, 15), CPTAB(15, 15) /BT/ NT
               1/MW/ WM(15)
000012          DIMENSION SUM(15), V(15), Y(15), VR(15), WMR(15), PHI(15), YPHI(15
               1), CP(15)
000012          NS = NSP
000013          DO 1 I = 1, NS
000015        1 CALL LN3RIN(T, V(I), TTAB, VSP(1, I), DYDX, NT)
000035          CALL COMP(OFR, P, Y, NS)
000037            SUMVIS = 0.
000040          DO 20 I = 1, NS
000045          IF (Y(I) .LT. .001) GO TO 20
000051        9   SUM(I) = 0.
000053          DO 10 J = 1, NS
000055            VR (J) =  V(I)/ V(J)
000062            WMR (J) =  WM(J) / WM(I)
000067            PHI(J) = (1. + SQRT (VR(J)* SQRT (WMR(J))))**2/(2.828 * SQRT  (
               1              1. + 1. / WMR(J)))
000112           YPHI(J) =  Y(J) * PHI(J)/Y(I)
000120       10   SUM(I) = SUM (I) + YPHI(J)
000132            SUMVIS =  SUMVIS  + V(I) / SUM(I)
000136       20   CONTINUE
000141            VISG = SUMVIS /1.E6
000142           DO 25 I = 1, NS
000144       25 CALL LN3RIN(T, CP(I), TTAB, CPTAB(1, I), DCPDT, NT)
000164            SIGA = 0.
000165            SIGB=  0.
000166           DO 30 I = 1, NS
000167            SIGA = SIGA  +  Y(I) * CP(I)
000174       30   SIGB = SIGB  +  Y(I) * WM(I)
000202            CPG  = SIGA / SIGB
000204            TKG  = VISG * ( CPG +  2.484/ SIGB)
000207            RETURN
000207            END
```

```
              SUBROUTINE DIFFU(OFR,P,T,VPO2,I,DFU,NSPEC)
        C
        C          THIS SUBROUTINE  CALCULATES THE DIFFUSIVITY OF OX THRU
        C          MIX(I=1) AND FUEL THRU MIX (I=2)
        C
000012        COMMON/C/ TA(1000)
000012        DIMENSION WTMOL(2), OMEGT(29),XKTOET(29),Y(15)
000012        EQUIVALENCE  ( WTMOL(1),TA(48))
000012        COMMON/DIFFUS/EPSI(15,2),SIGMA(15,2),EPSOF(2),SIGOF(2)/MW/WM(15)
000012        DATA KS/0/,NPTS/29/
000012        DATA OMEGT/   2,662 ,   2,318,   2,066,   1,877,   1,720,
             *    1,612,    1,517,    1,439,   1,32,    1,233,   1,167,
             *    1,116,    1,075,    0,9996,  0,949,   0,912,   0,8836,
             *    0,561,    0,8422,   0,8124,  0,7712,  0,7424,  0,6640,
             *    0,6232,   0,596,    0,5756,  0,5596,  0,5352,  0,517/
000012        DATA XKTOET/  .3,       .4,      .5,      .6,      .7,
             *    .8,       .9,       1,0,     1,2,     1,4,     1,6,
             *    1,8,      2,0,      2,5,     3,0,     3,5,     4,0,
             *    4,5,      5,0,      6,0,     8,0,     10,0,    20,0,
             *    30,0,     40,0,     50,0,    60.,     80,0,    100,0/
000012        IF(KS)100,10,100
        C
        C          CALC  CONSTANST FOR THIS PROPELLANT SYSTEM
        C
000013     10 NS=NSPEC
000015        KS=1
000016        NSAVE=1
000017        DO 20 K=1,NS
000020        EPSI(K,2)=EPSI(K,1)
000023        SIGMA(K,2)=SIGMA(K,1)
000025    20  CONTINUE
000027        DO 50 J=1,2
000031        DO 50 K=1,NS
000032        EPSI(K,J)= SQRT(EPSOF(J)*EPSI(K,J))
000042        SIGMA(K,J)=(0,5*(SIGOF(J)+SIGMA(K,J)))**2/0,00422188/
             1    SQRT( 1,0/WTMOL(J) + 1,0/WM(K))
000063   50   CONTINUE
000073  100   CALL COMP(OFR,P,Y,NS)
000075        SUMD=0,0
000076        XNUM=1,0- VPO2/P
000104        T1=T/1,8
000106        T32=T1*SQRT(T1)
000111        DO 300 K=1,NS
000116        Y(K)=Y(K)*(P-VPO2)/P
000122        F= T1/EPSI(K,I)
000125        CALL LNBRIN(F,OMEG,XKTOET,OMEGT,DYDX,NPTS)
000131        PD=T32/OMEG/SIGMA(K,I)
000142        SUMD=SUMD +Y(K)/PD
000146  300   CONTINUE
000150        DFU= XNUM/SUMD/P
000152        RETURN
000152        END
```

REFERENCES

1. Dippery, D. F., J. H. Rupe, R. N. Porter, and D. D. Evans, "On the Evolution of Advanced Propulsion Systems for Spacecraft," Tech.Rept. No. 32-735 (Section II), Jet Propulsion Laboratory, Pasadena, Calif. July 1965.

2. Elverum, G. W., Jr. and P. Staudhammer, "The Effect of Rapid Liquid-Phase Reactions on Injector Design and Combustion in Rocket Motors," Progress Rept. 30-4, Jet Propulsion Laboratory, Pasadena, California, August 1959.

3. Johnson, B. H., "An Experimental Investigation of the Effects of Combustion on the Mixing of Highly Reactive Liquid Propellants," Tech.Rept. No. 32-689, Jet Propulsion Laboratory, Pasadena, California, November 1967.

4. Burrows, M. C., "Mixing Reaction of Hydrazine and Nitrogen Tetroxide at Elevated Pressure," AIAA J, Vol. 5, No. 9, pp 1700-1701, Sept. 1967.

5. Lawver, B. R. and B. P. Breen, "Hypergolic Stream Impingement Phenomena, Nitrogen Tetroxide/Hydrazine," Dynamic Science Rept. NASA-CR-72444, Monrovia, California, October 1968.

6. Kushida, R. and J. Houseman, "Criteria for Separation of Impinging Streams of Hypergolic Propellants," Tech.Memo 33-395, Jet Propulsion Laboratory, Pasadena, California, July 1968.

7. Somogyi, D. and C. E. Feller, "Liquid Phase Heat Release Rates of the Systems Hydrazine-Nitric Acid and Unsymmetrical-Dimethyl Hydrazine-Nitric Acid," NASA TN D-469, September 1960.

8. Weiss, R. and R. D. Klopotek, "Experimental Evaluation of the Titan III Transtage Engine Combustion Stability Characteristics," AFRPL-TR-66-51, March 1966 Also see Chew, T., R.D. Klopotek, and R. Weiss, 7th Liq. Propulsion Sysposium, Denver Col., 1965.

9. Clayton, R. M., "Some Effects of Near-Wall Injection on Steady and Nonsteady Liquid Rocket Combustion Behavior," 4th ICRPG Combustion Conference, Vol. I, October 1967

10. Beltran, M. R., B. P. Breen, et al "Liquid Rocket Engine Combustion Instability Studies," Dynamic Science Rept. AFRPL-TR-66-125, Monrovia, California, July 1966.

11. Abbe, C. J., C. W. McLaughlin, R. R. Weiss," Influence of Storable Propellant Liquid Rocket Design Parameters on Combustion Instability," Spacecraft & Rockets, J. Vol. 5, No. 5, P 584, May 1968.

12. Mills, T. R., E. A. Tkachenko, B. R. Lawver, and B. P. Breen, "Transients Influencing Rocket Engine Ignition and Popping," Dynamic Science Rept. NAS7-467, January 1969.

13. Burrows, M C. "Mixing and Reaction Studies of Hydrazine and Nitrogen Tetroxide Using Photographic and Special Techniques," NASA TM X-52244, 1966.

14. Jaye, F. C. and J. A. Blauer, "Reactions of the Chlorine Fluorine Interhologens with Hydrogen," Tech.Rept. AFRPL-TR-69-62, April 1969.

15. Sawyer, R. F. and I. Glassman, Eleventh Symposium on Combustion, p 861, 1966.

16. Weiss, H.G., H. D. Fisher, M. Gerstein, and B.H. Johnson, "Modification of the Hydrazine-Nitrogen Tetroxide Ignition Delay." AIAA J. pp 2222, Dec. 1964.

17. Dickerson, R., K. Tate, N. Barsic, "Correlation of Spray Injector Parameters with Rocket Engine Performance," Tech.Rept. AFRPL TR-68-147, Rocketdyne, A Division of N.A. Rockwell Corp., June 1968.

18. Ratliff, A. W., "The Effect of Nozzle Flow Striations on Engine Performance," LMSC/HREC A784646, Lockheed Missiles and Space Company, Huntsville, Ala., August 1967.

19. Hersch, M., "A Mixing Model for Rocket Engine Combustion," NASA Tech.Note NASA TN D-2881, June 1965.

20. Priem, R. J. and M. F. Heidmann, "Propellant Vaporization as a Design Criterion for Rocket Engine Combustion Chambers," NASA TR R-67, 1960.

21. Beltran, M. R., B. P. Breen, and M. Gerstein, "Combustion Stability Limits Calculated Utilizing a Nonlinear Model," Final Rept. NAS7-366, NASA/Lewis Research Center, August 1966.

22. Beltran, M.R., B P. Breen, et al, "Liquid Rocket Engine Combustion Instability Studies," Final Rept. AFRPL-TR-66-125, July 1966.

23. Breen, B. P. and M. R. Beltran, "Steady-State Droplet Combustion with Decomposition: Hydrazine/NTO," presented at AIChE 61st National Meeting, Houston, Texas, February 1967.

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Dynamic Science, a Division of Marshall Industries 1900 Walker Ave., Monrovia, California	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Technical Report - 8 April 1968 to 15 January 1969

5. AUTHOR(S) (Last name, first name, initial)
Breen, B. P.
Lawver, B. R.
Zung, L. B.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS

8a. CONTRACT OR GRANT NO. F04611-68-C-0040 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) SN-121 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Air Force Rocket Propulsion Laboratory Research and Technology Division

13. ABSTRACT

Mixing and separation criteria of hypergolic propellants are characterized by a chemical reaction time and a mixing time. Separation limit is defined by assuming the two characteristic times to be equal. Experimental results with hydrazine and nitrogen tetroxide propellants agree very well with this separation limit, and also show that the effect of chamber pressure is not significant. MMH and A-50 with nitrogen tetroxide give separation limits at higher propellant temperatures. It appears that stream separation always occurs by impinging compound A and hydrazine with oxidizer and fuel temperatures varying between 0°F to 30°F and 40°F to 60°F.

A second work area of the project was concerned with the extension of the Steady-State Combustion Computer Model. The computer program was generalized to allow increased versatility in running various propellant systems. The numerical procedures and organizations of the program were substantially improved. Propellant property values were gathered for several systems of current interest. A computer program listing is presented.

DD FORM 1473

Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	
Impingement						
Hypergolic Propellant						
Hydrazine						
MMH						
A-50						
Compound A						
Nitrogen Tetroxide						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY, LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ______."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ______."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ______."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. *SUPPLEMENTARY NOTES: Use for additional explanatory notes.*

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13 ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.